US011280997B1

(12) **United States Patent**
Gao

(10) **Patent No.: US 11,280,997 B1**
(45) **Date of Patent: Mar. 22, 2022**

(54) **LOW-OBLIQUITY PUPIL RELAY FOR TILTABLE REFLECTORS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 280 days.

(21) Appl. No.: **16/664,028**

(22) Filed: **Oct. 25, 2019**

(51) **Int. Cl.**

G02B 26/08	(2006.01)
G02B 26/10	(2006.01)
G02B 5/10	(2006.01)
G02B 5/30	(2006.01)
G02B 27/30	(2006.01)
G02B 27/14	(2006.01)
G02B 27/00	(2006.01)
G03H 1/02	(2006.01)
F21V 8/00	(2006.01)
G02B 27/28	(2006.01)

(52) **U.S. Cl.**
CPC ***G02B 26/101*** (2013.01); ***G02B 5/10*** (2013.01); ***G02B 5/3083*** (2013.01); ***G02B 6/0016*** (2013.01); ***G02B 6/0076*** (2013.01); ***G02B 26/0833*** (2013.01); ***G02B 27/005*** (2013.01); ***G02B 27/0075*** (2013.01); ***G02B 27/0093*** (2013.01); ***G02B 27/141*** (2013.01); ***G02B 27/283*** (2013.01); ***G02B 27/30*** (2013.01); ***G03H 1/0248*** (2013.01); *G03H 2222/36* (2013.01); *G03H 2240/15* (2013.01); *G03H 2250/38* (2013.01)

(58) **Field of Classification Search**
CPC G02B 26/101; G02B 27/0093; G02B 27/005; G02B 27/283; G02B 6/0076; G02B 27/30; G02B 6/0016; G02B 5/3083; G02B 5/10; G02B 27/0075; G02B 26/0833; G02B 27/141; G03H 1/0248; G03H 2222/36; G03H 2240/15; G03H 2250/38
USPC 359/199.4
See application file for complete search history.

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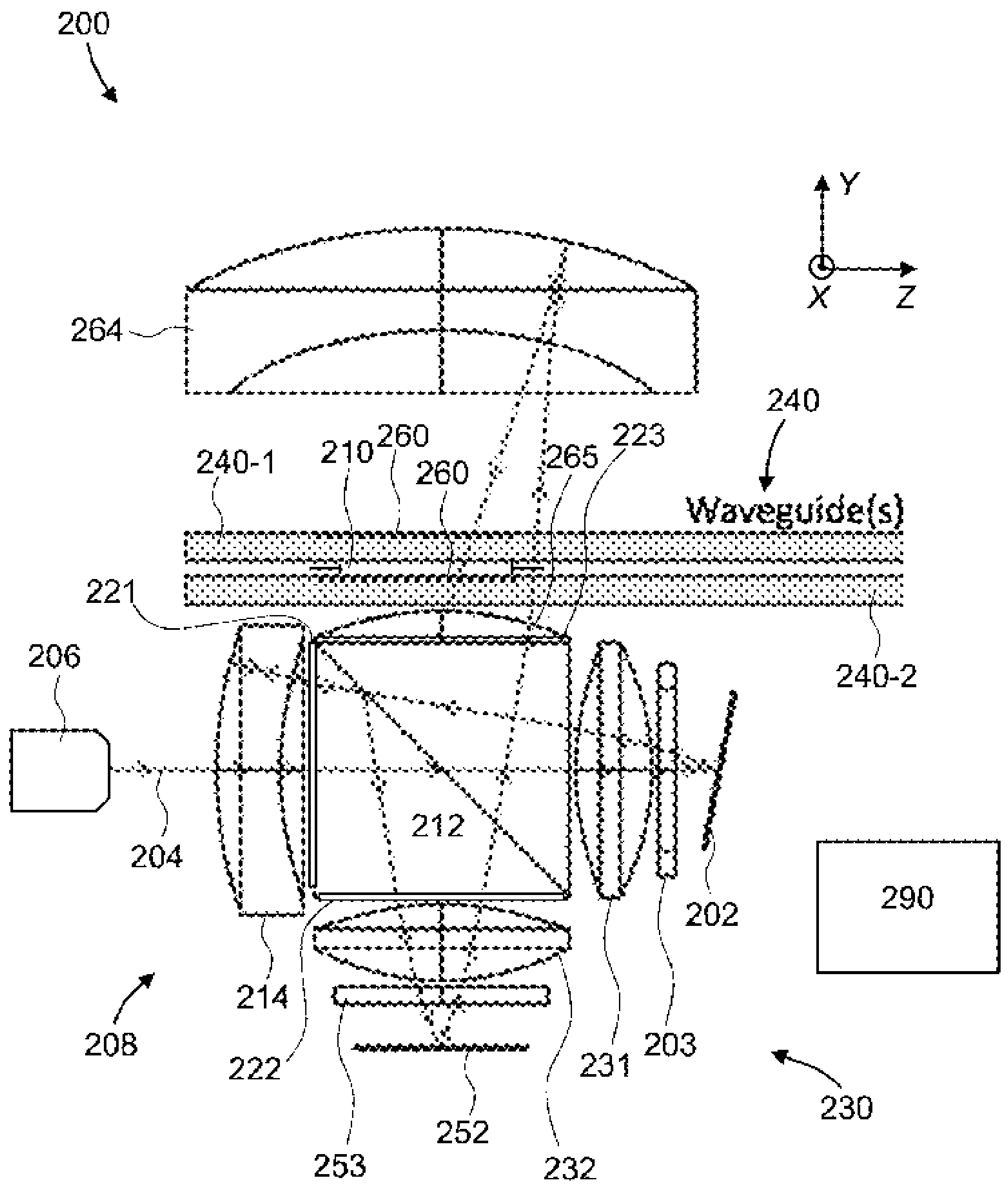
(57) **ABSTRACT**

A beam scanner of a near-eye display includes a pair of tiltable reflectors and a beam-folding pupil relay coupling the tiltable reflectors optically together. The beam-folding pupil relay includes a beamsplitter for receiving the light beam reflected by the first tiltable reflector, and a first curved reflector for receiving the light beam from the beamsplitter, and for reflecting the light beam back towards the beam-splitter. The beam-folded pupil relay is configured to couple the light beam reflected by the first curved reflector to the second tiltable reflector. A second curved reflector may be provided for coupling the light beam scanned by the tiltable reflectors to a pupil-replicating waveguide. A controller may be provided for scanning the light beam in coordination with operating the light source at varying levels of brightness or color.

20 Claims, 15 Drawing Sheets



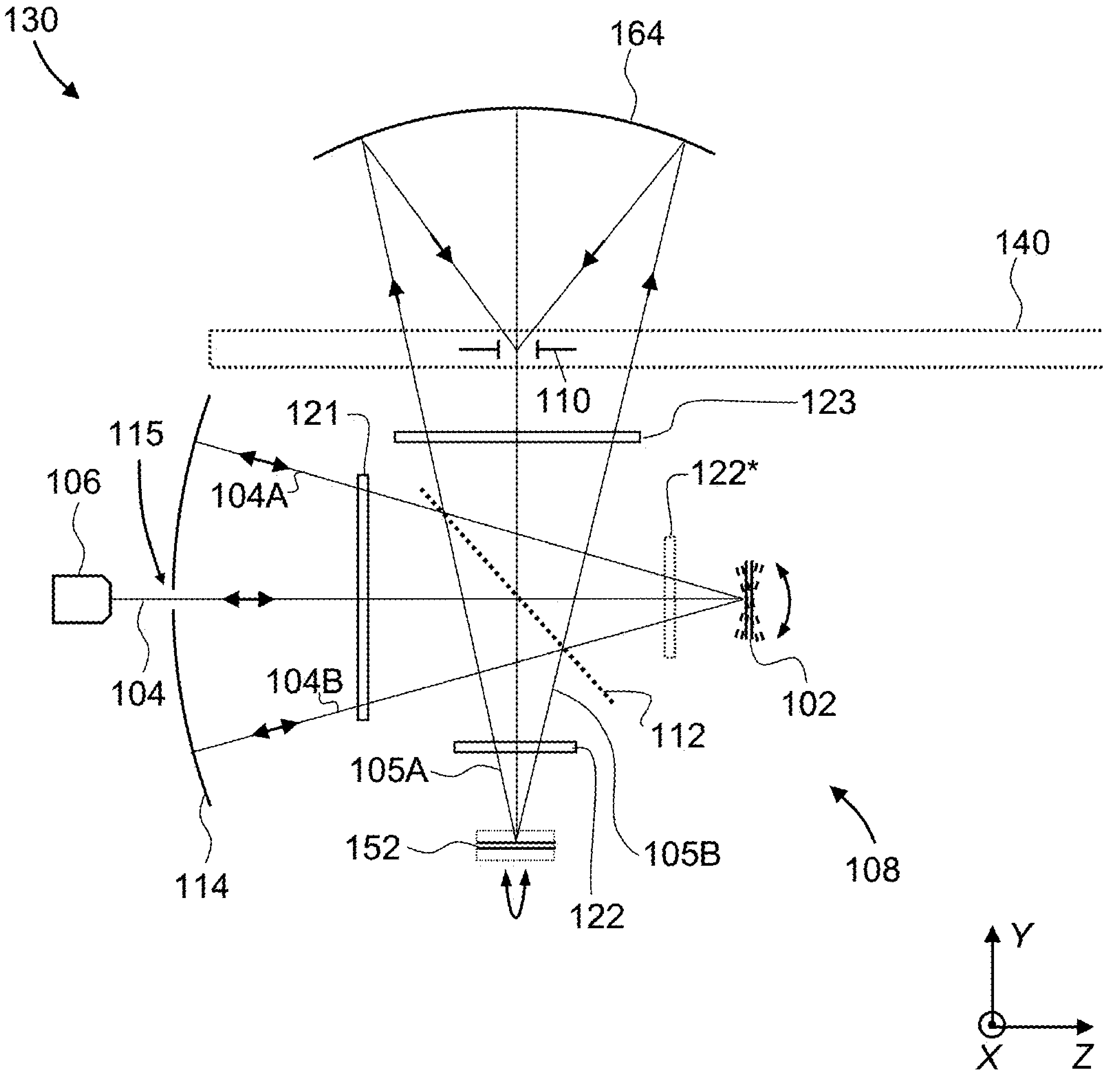

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FIG. 1

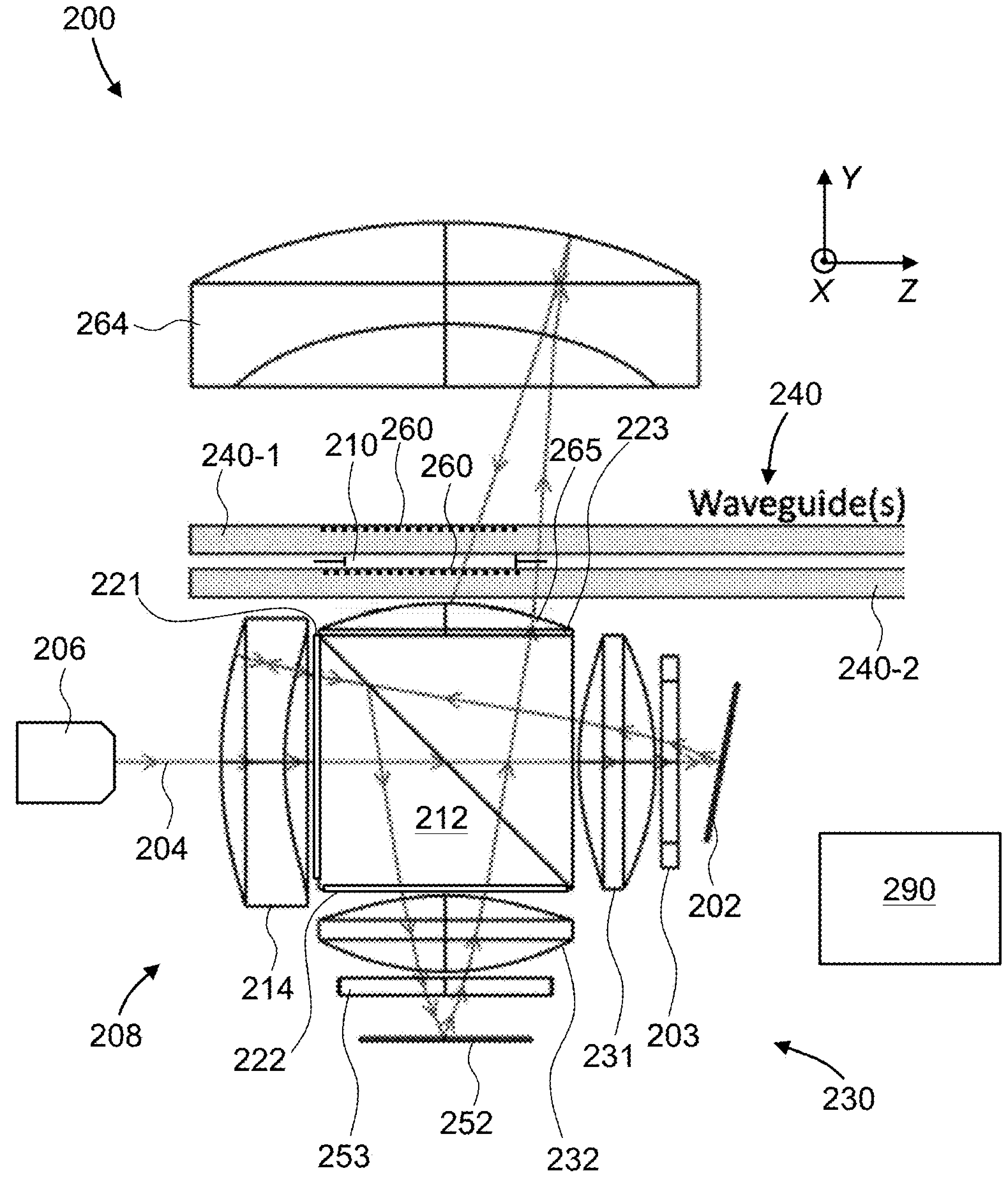
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FIG. 2A

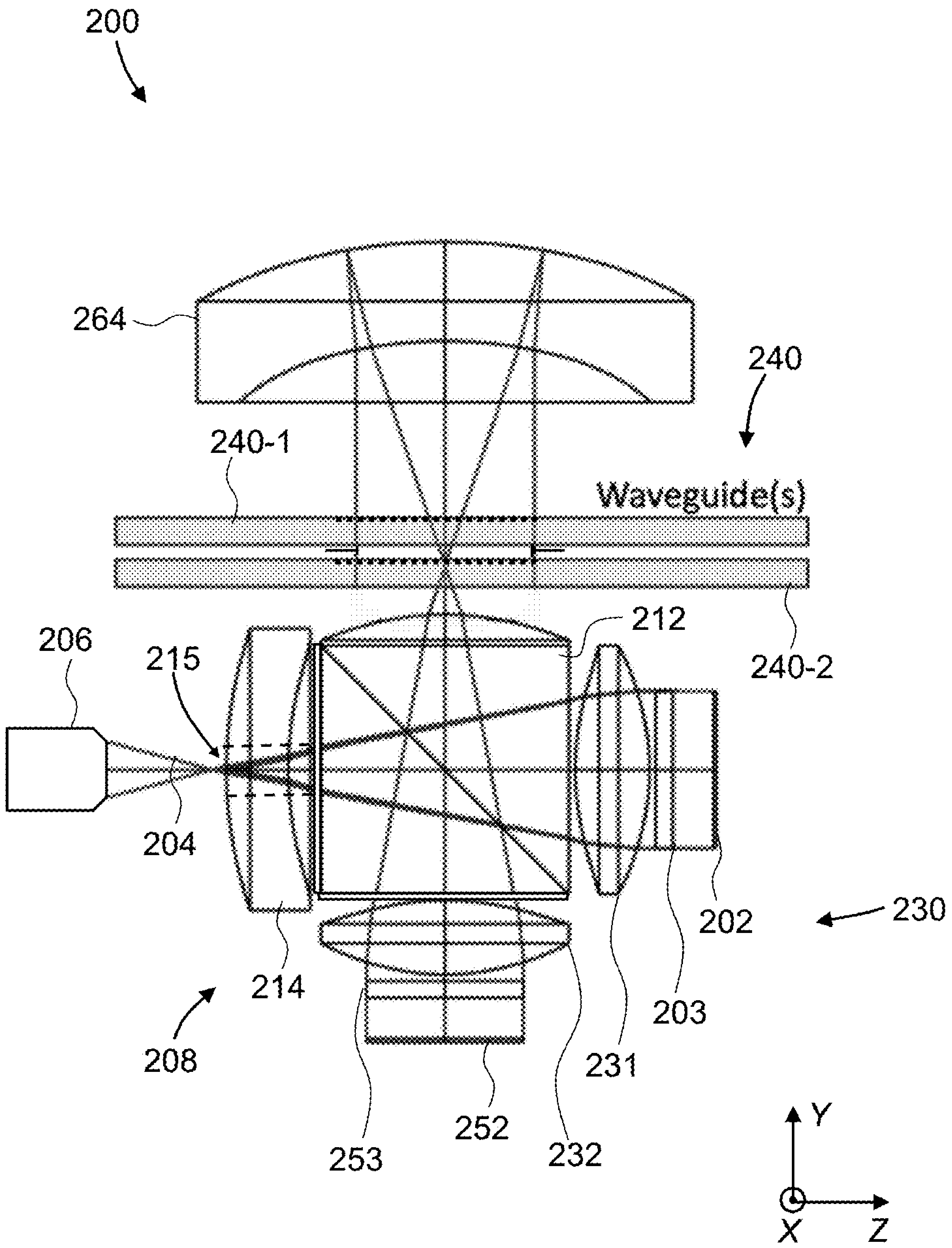
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FIG. 2B

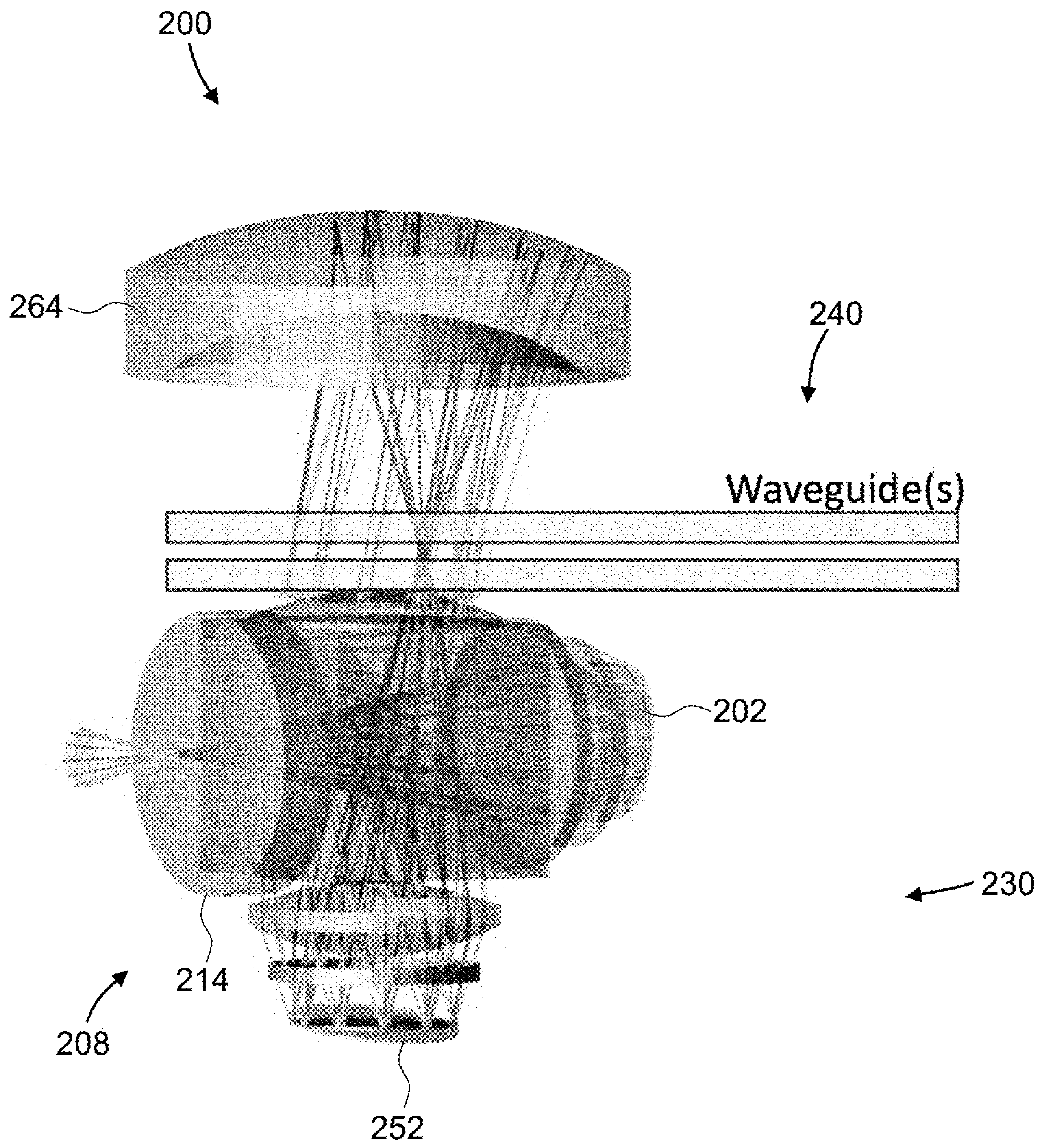
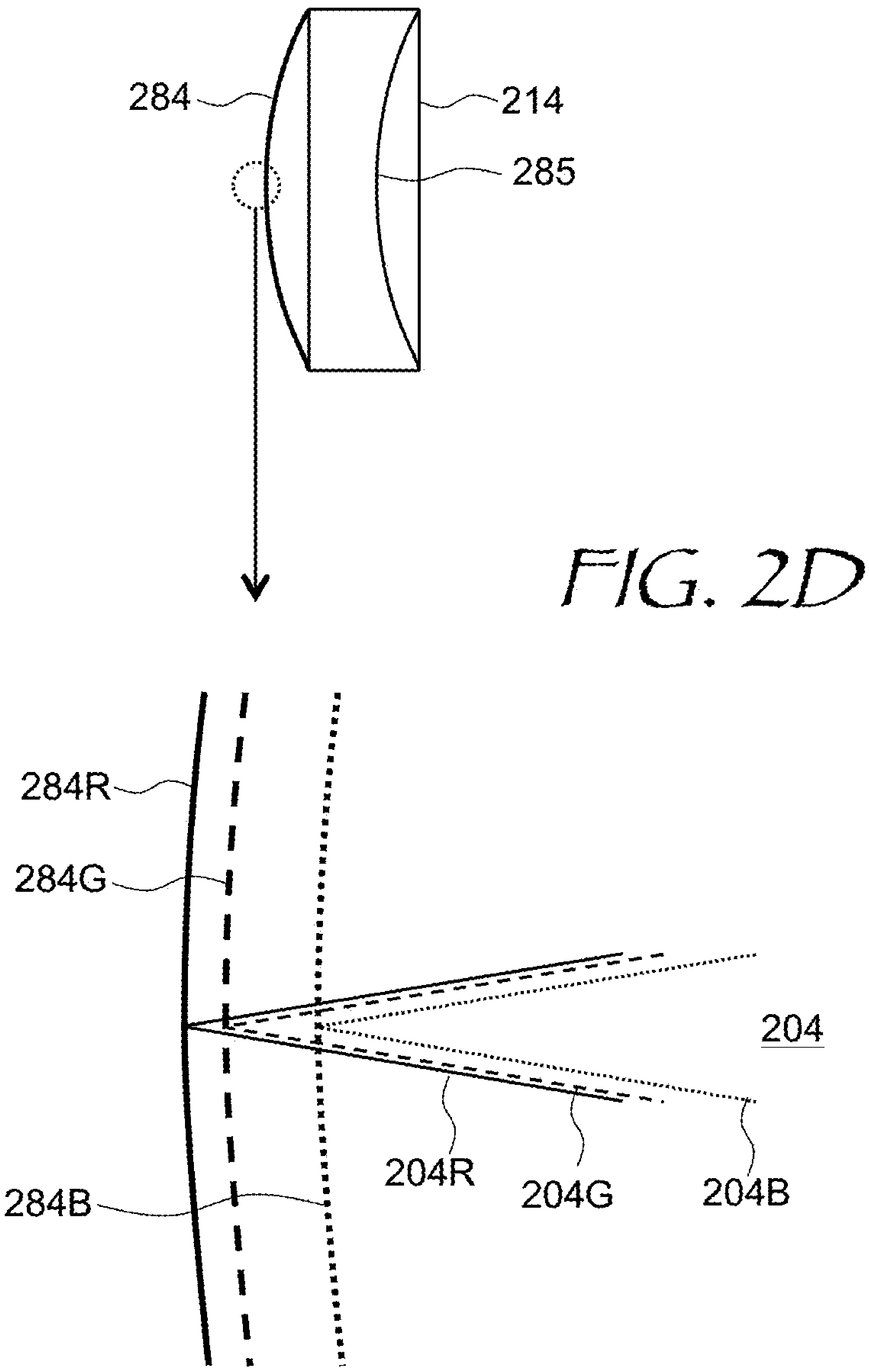


FIG. 2C



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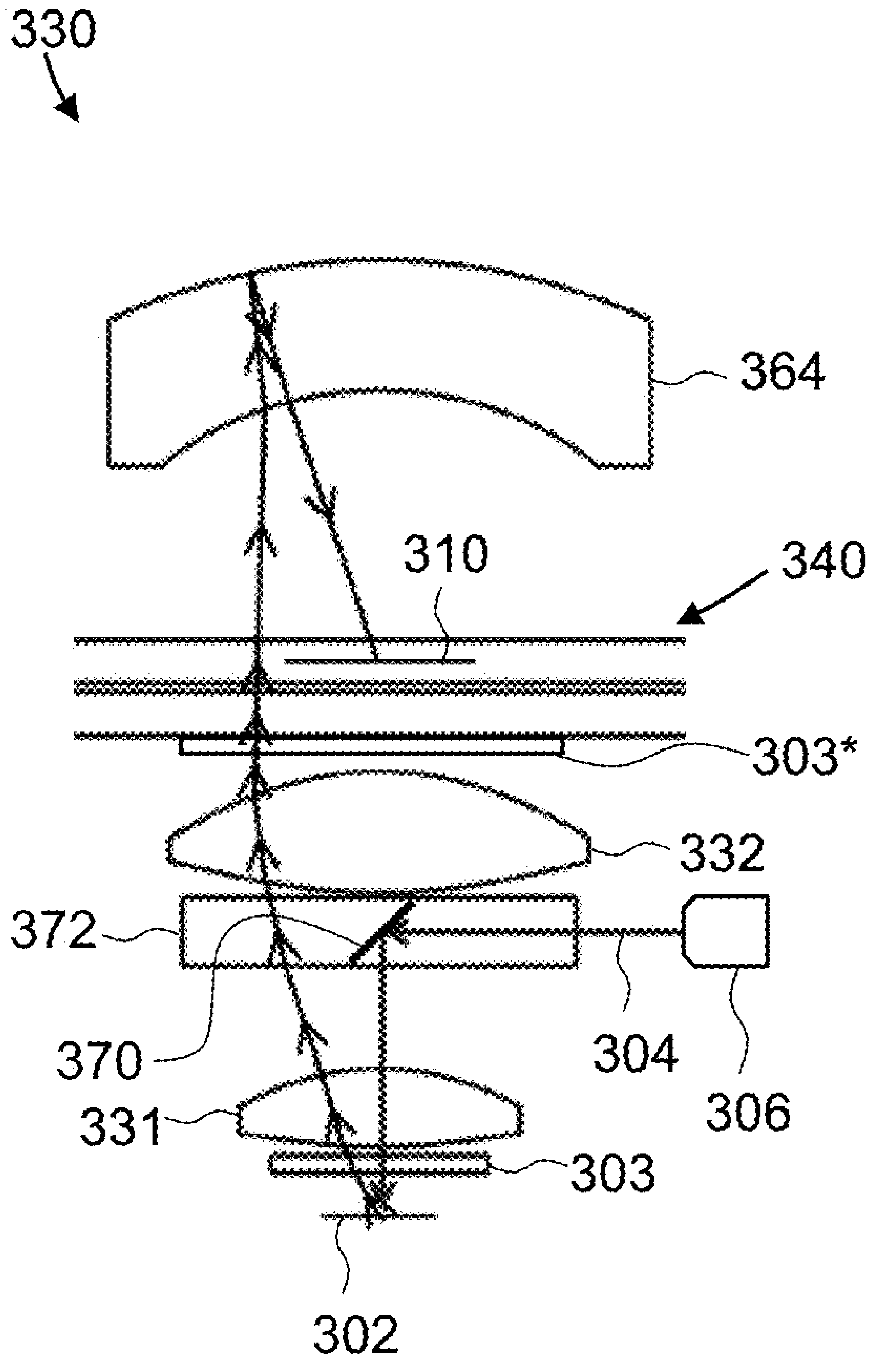
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FIG. 3A

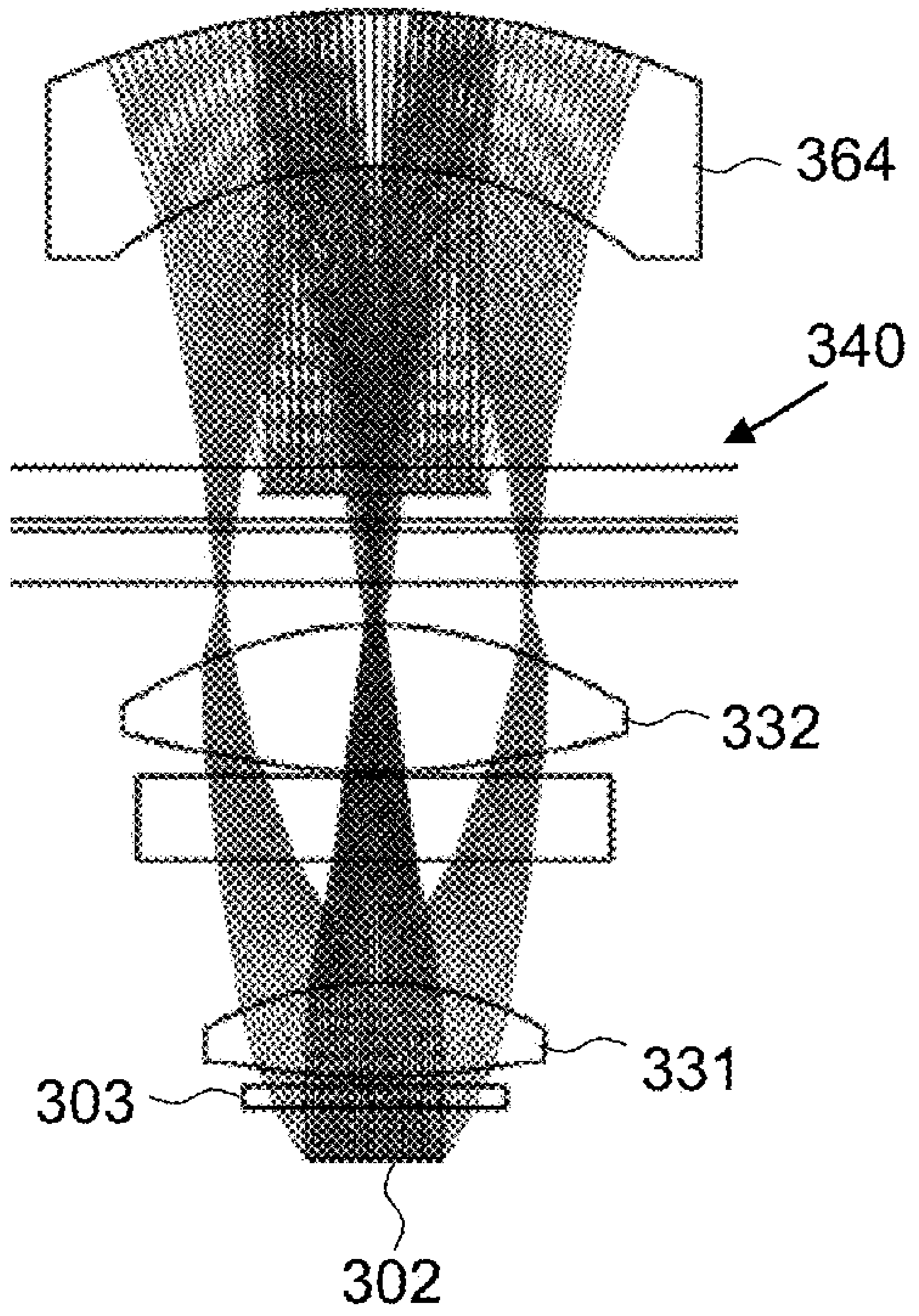
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FIG. 3B

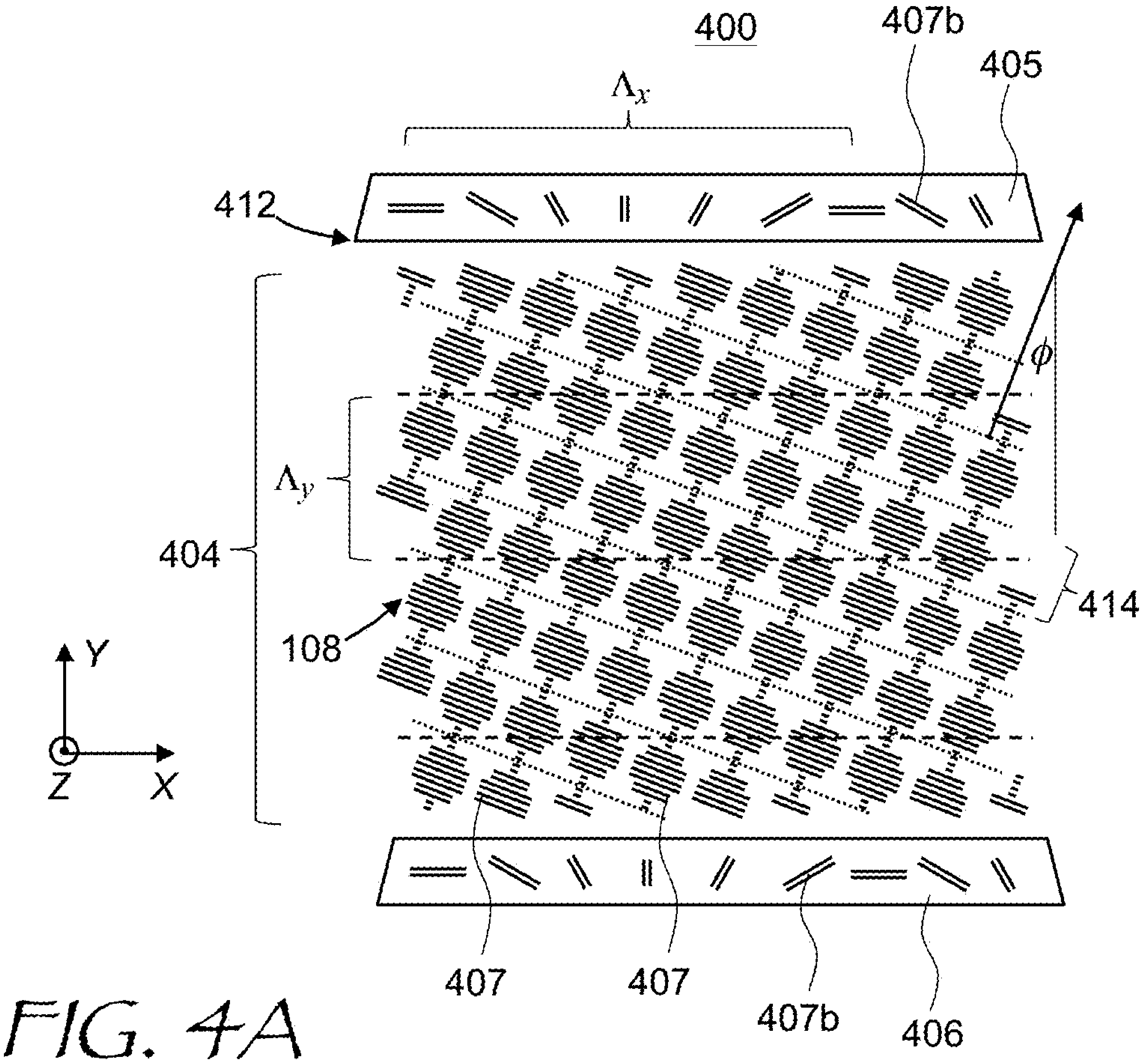
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FIG. 4A

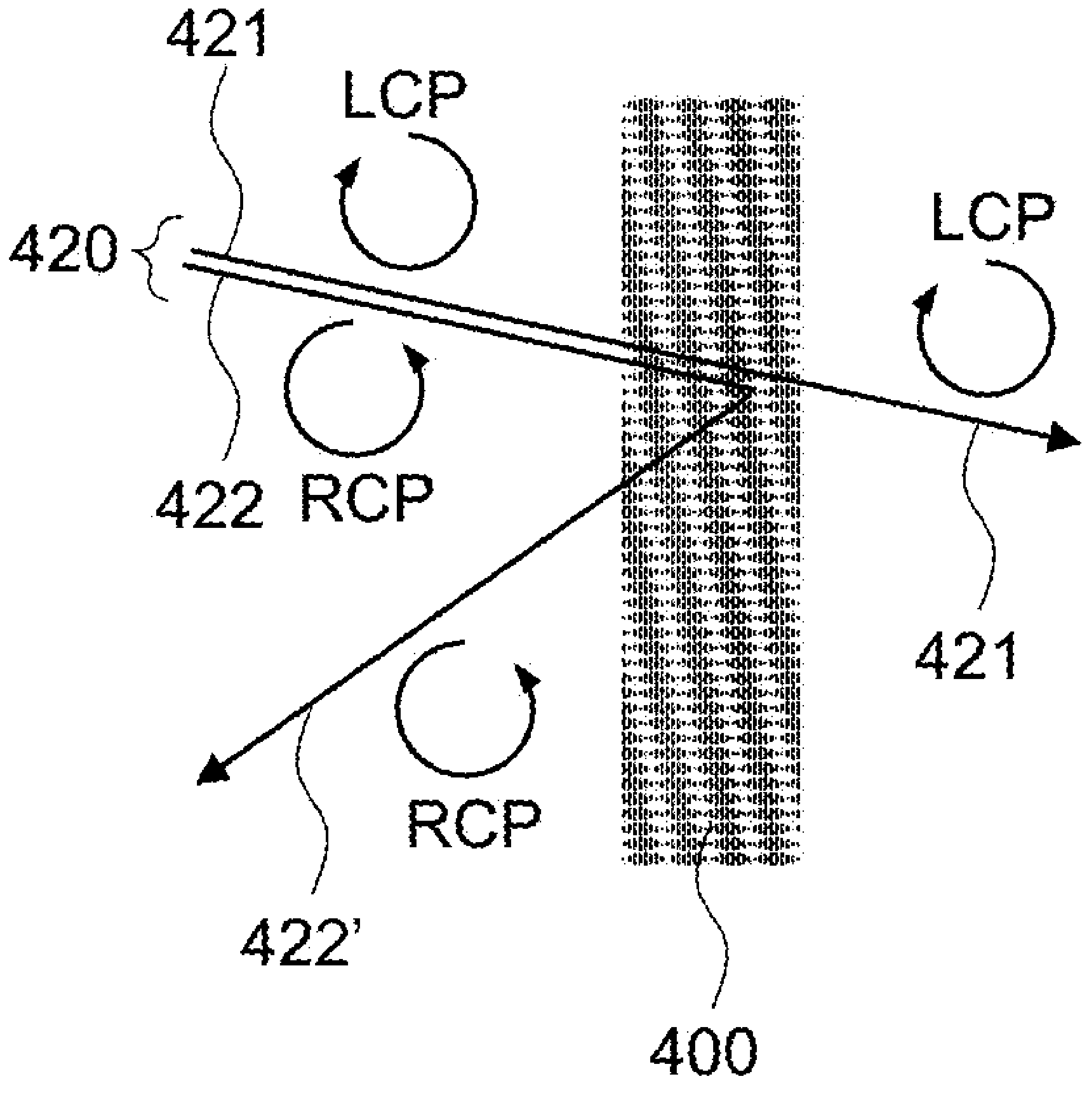
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FIG. 4B

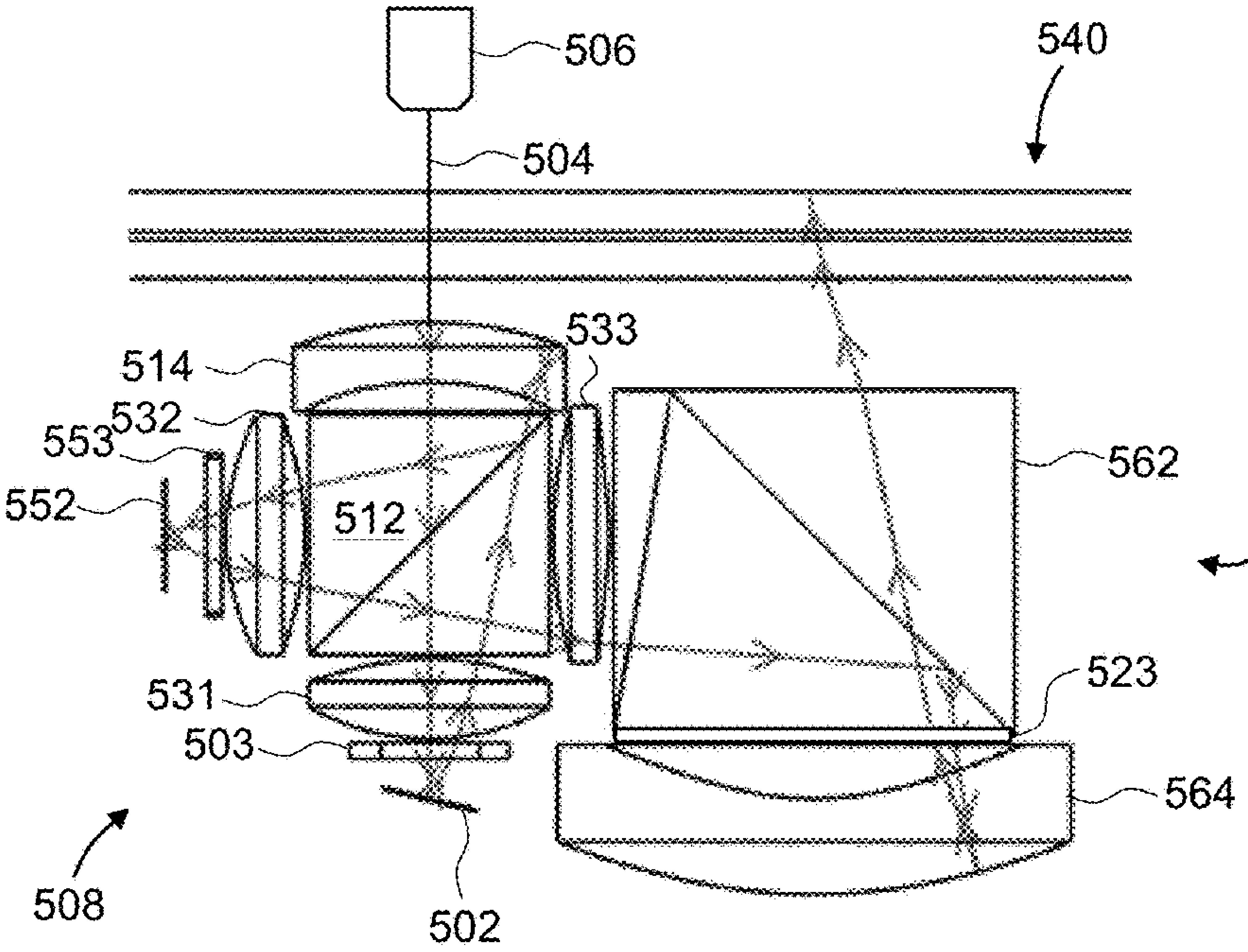
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FIG. 5A

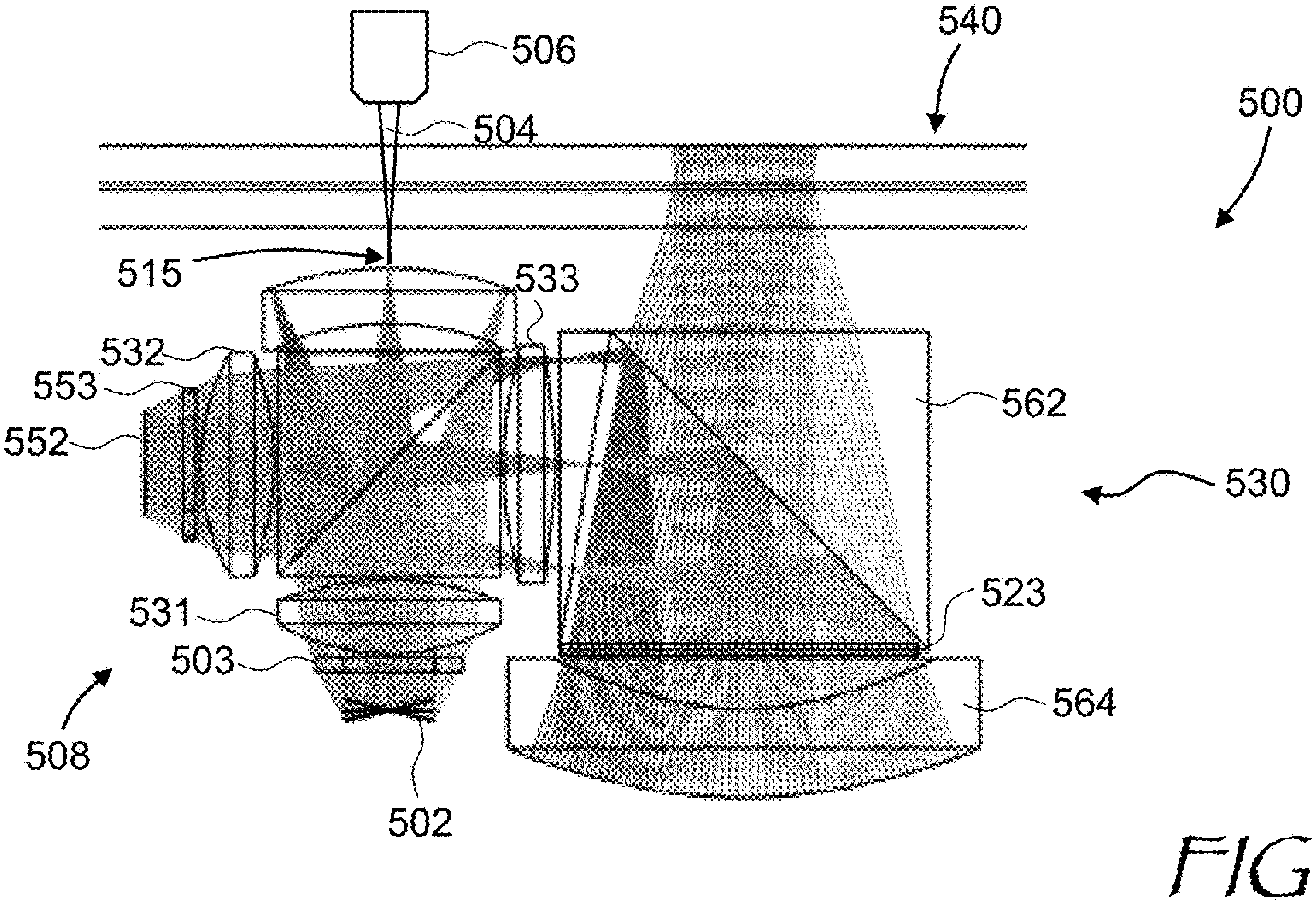
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FIG. 5B

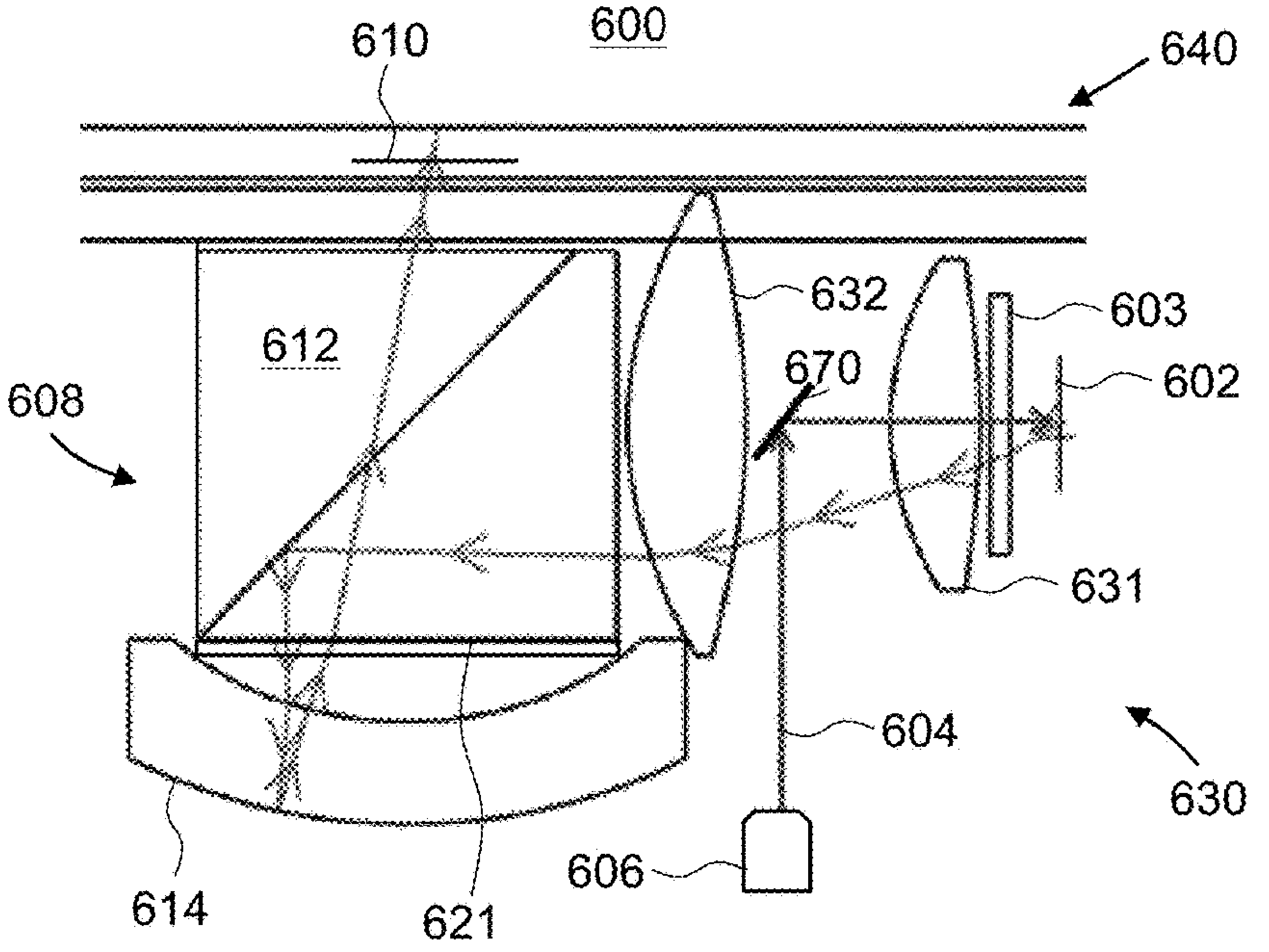
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FIG. 6A

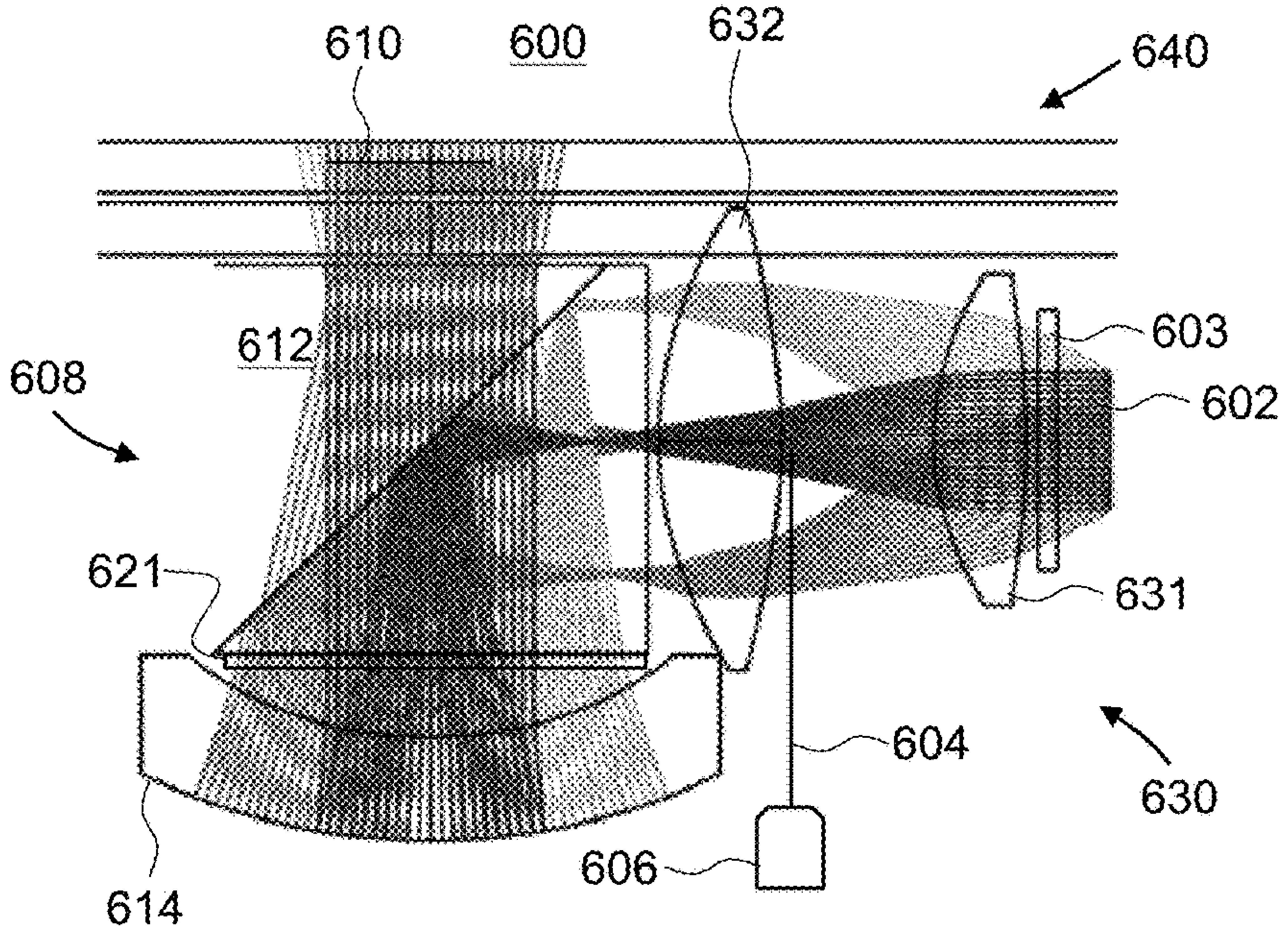
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FIG. 6B

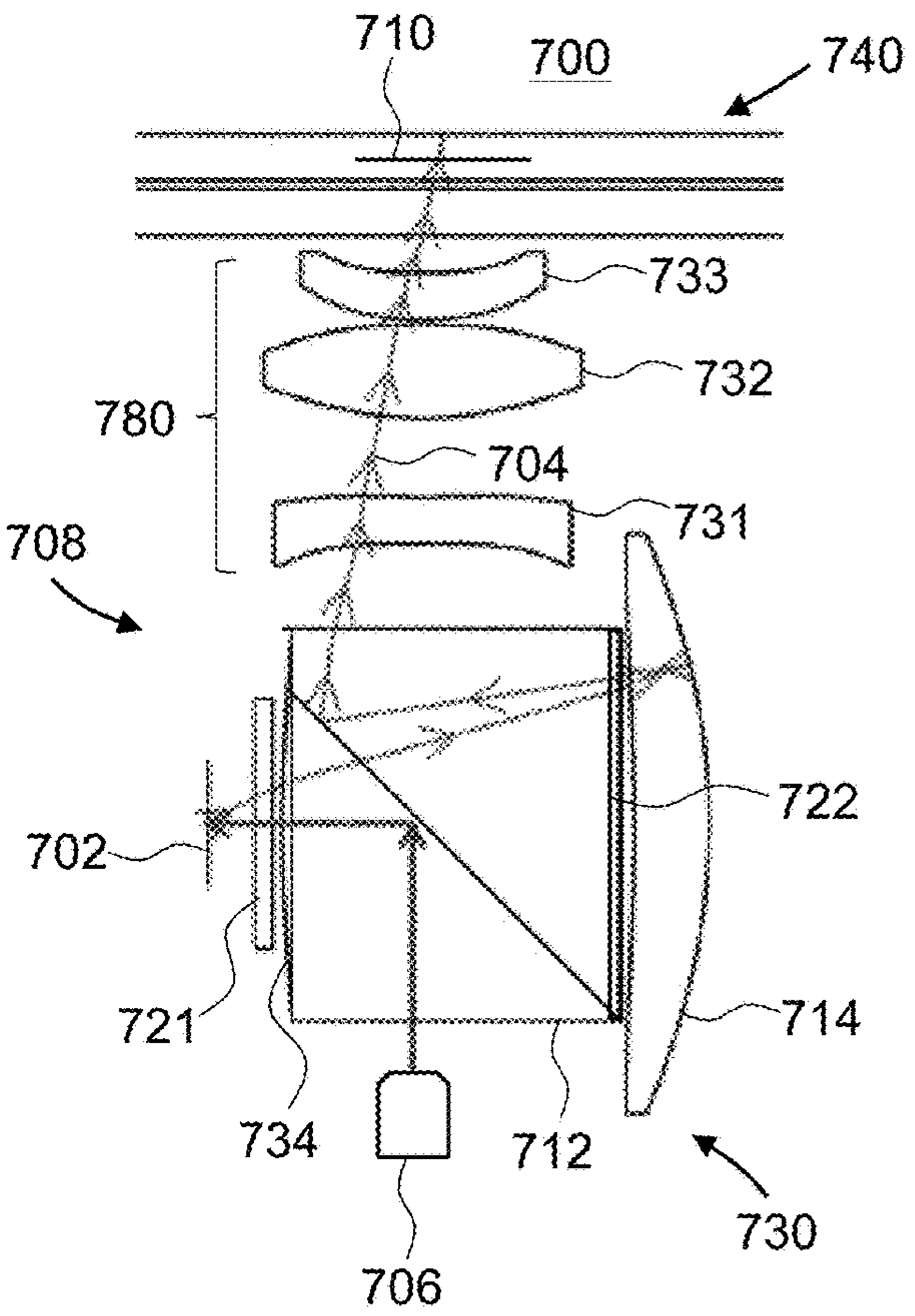
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FIG. 7A

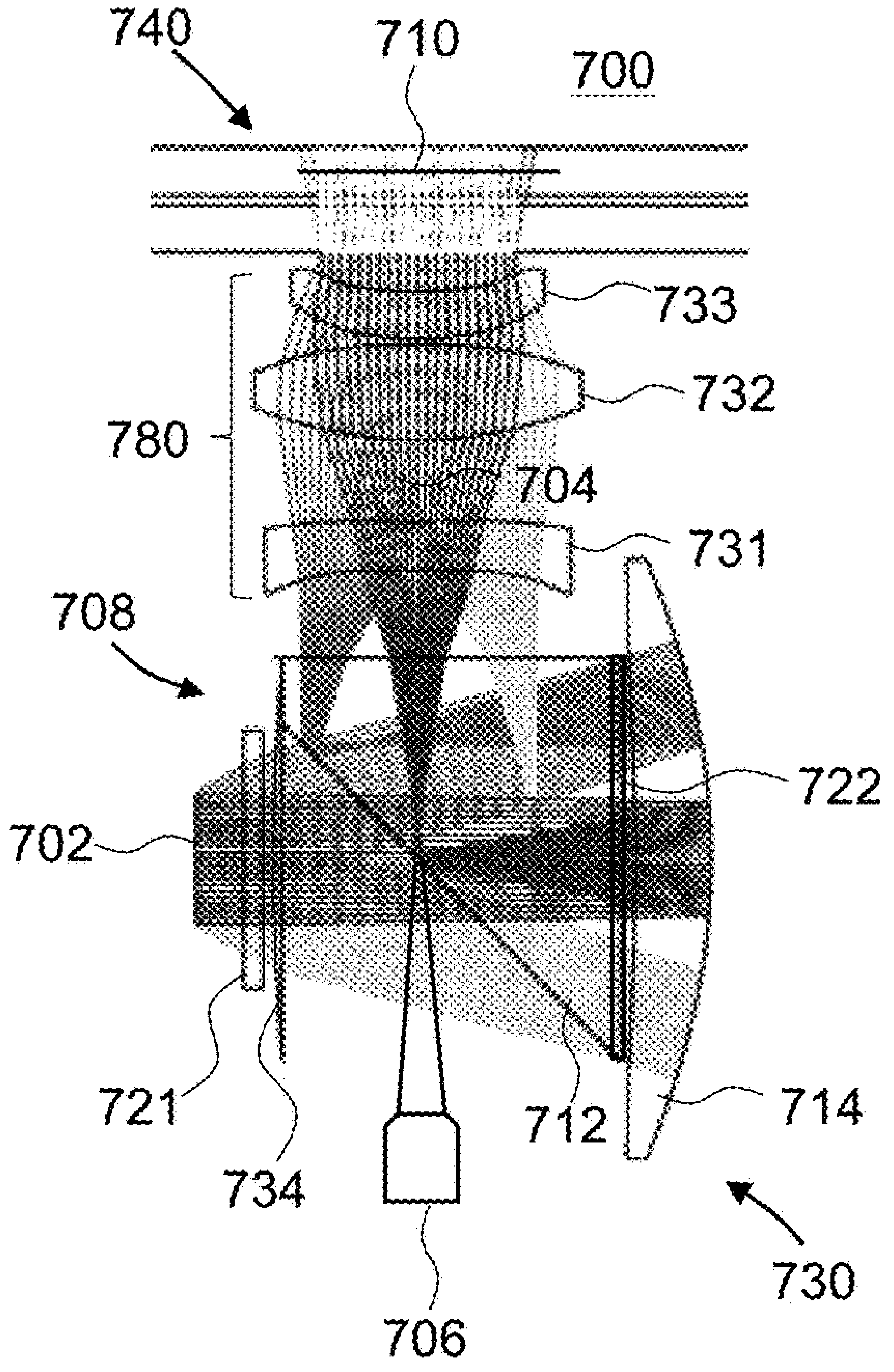
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FIG. 7B

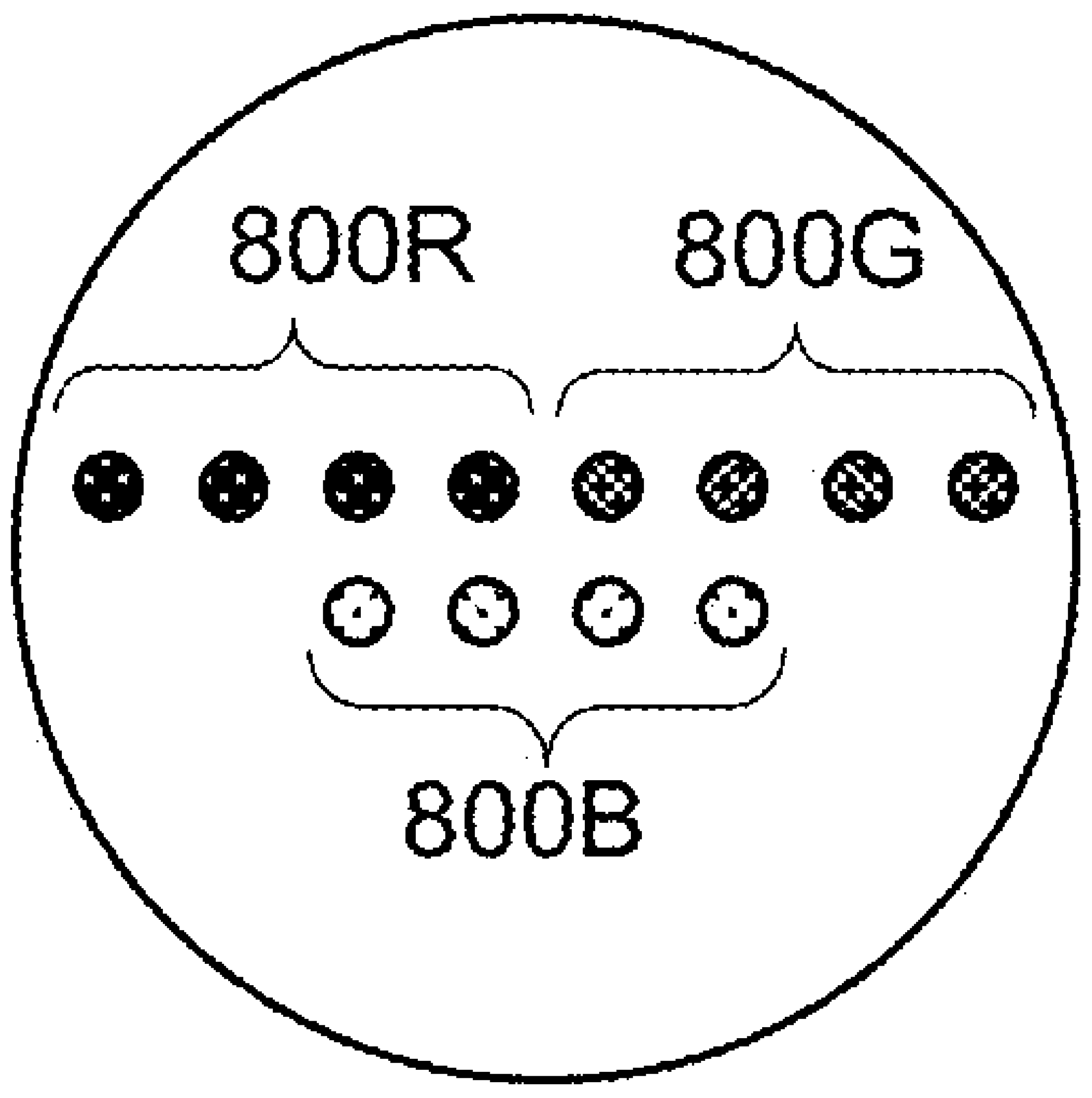


FIG. 8A

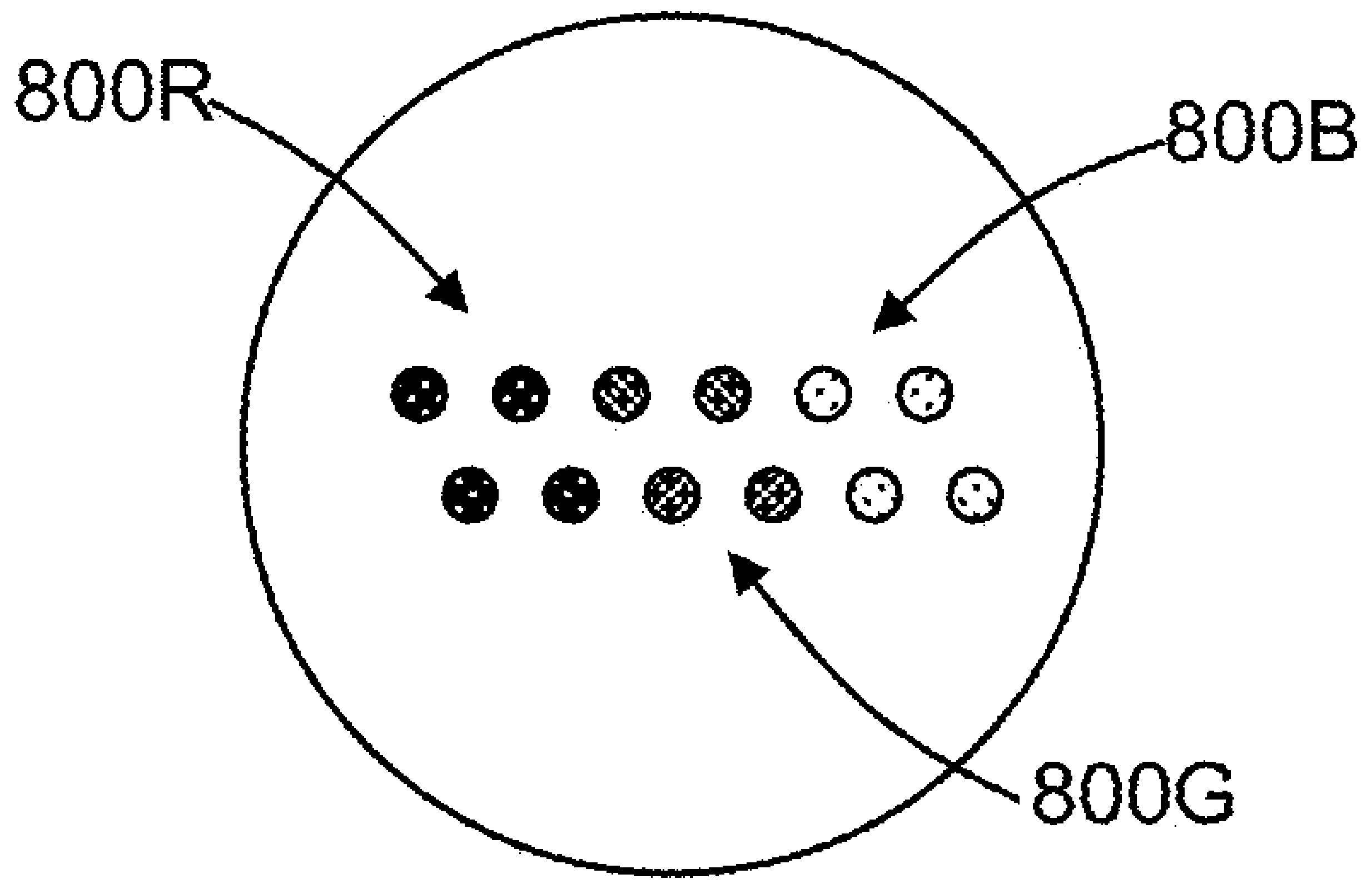


FIG. 8B

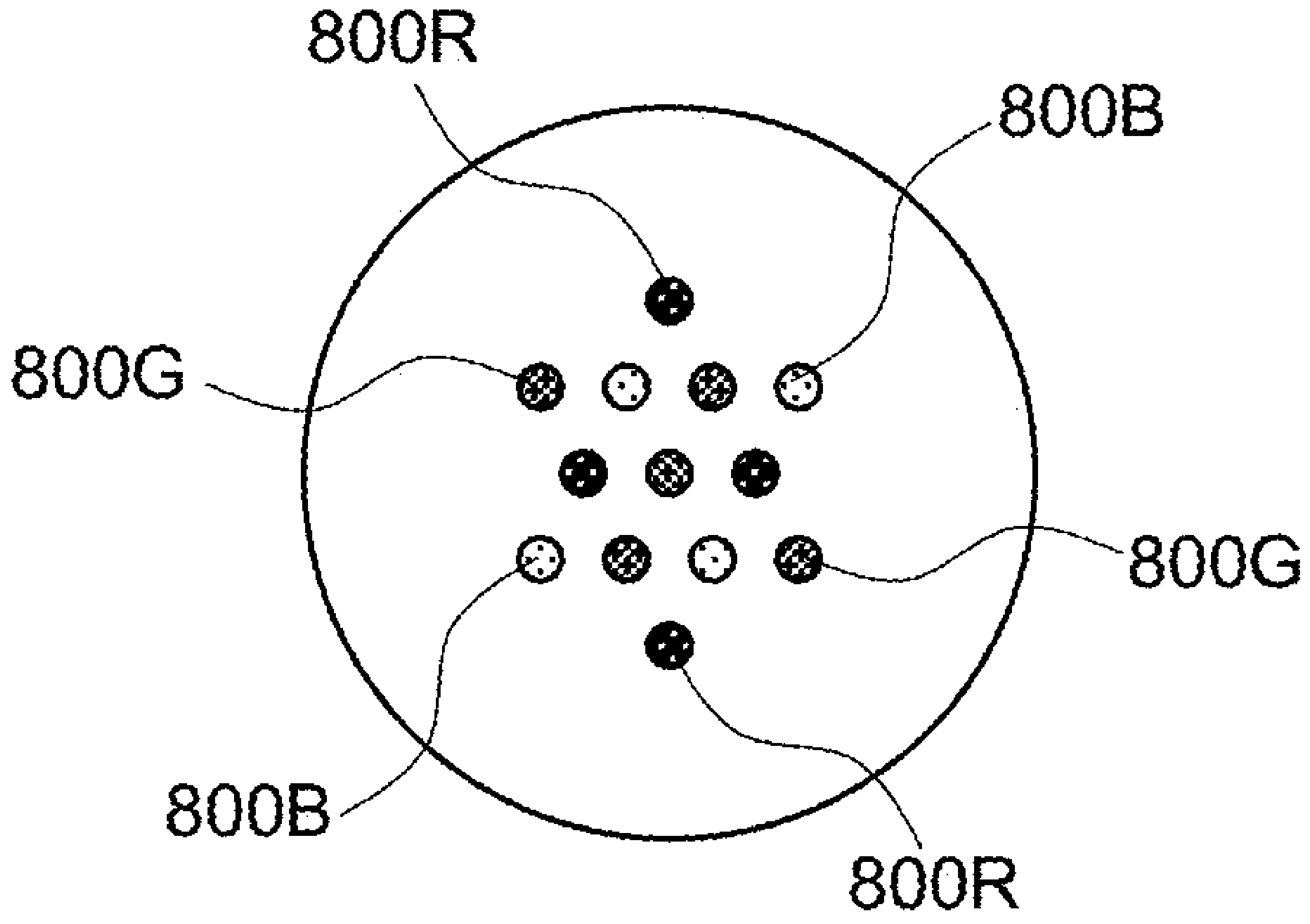


FIG. 8C

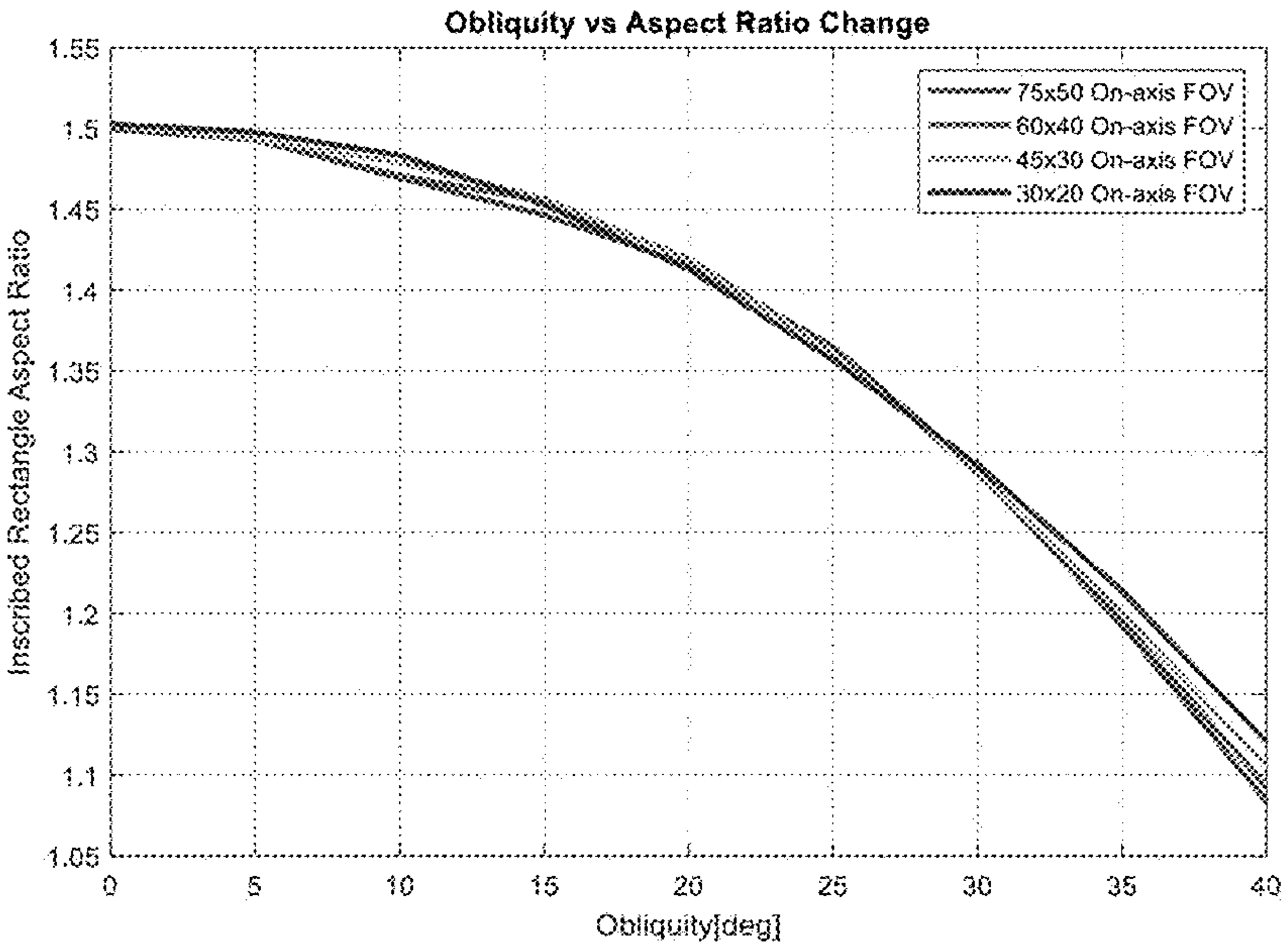


FIG. 9A

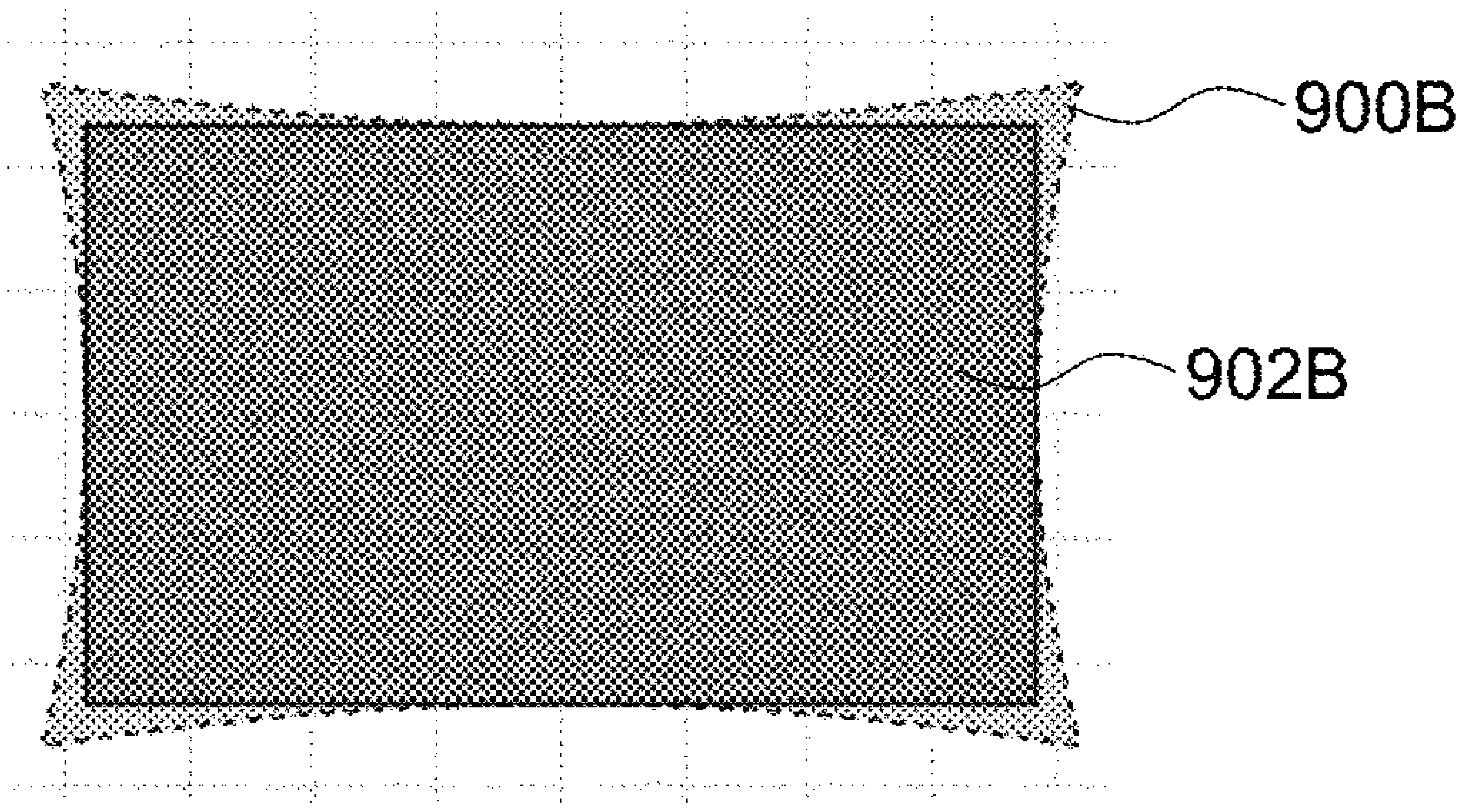


FIG. 9B

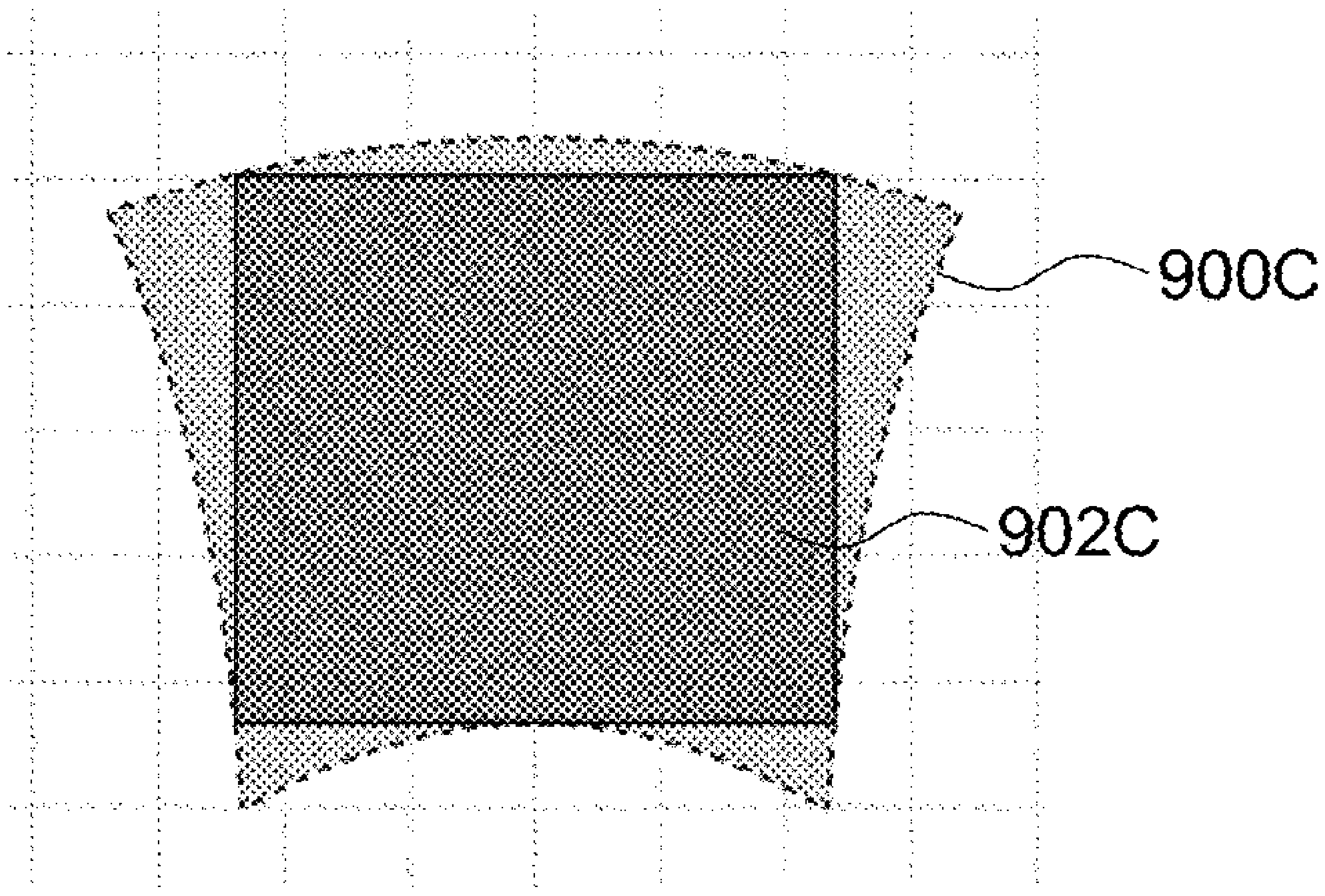


FIG. 9C

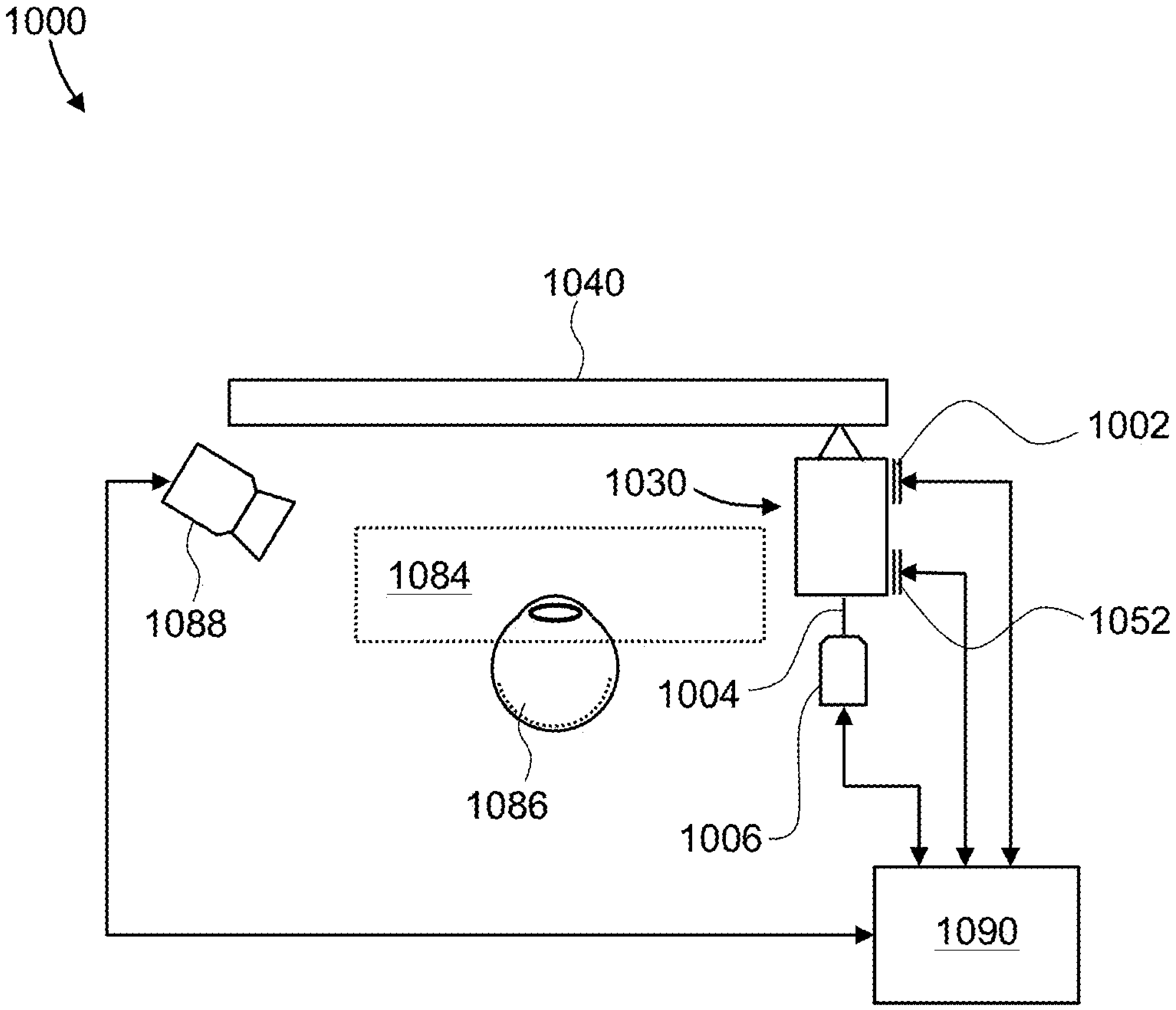
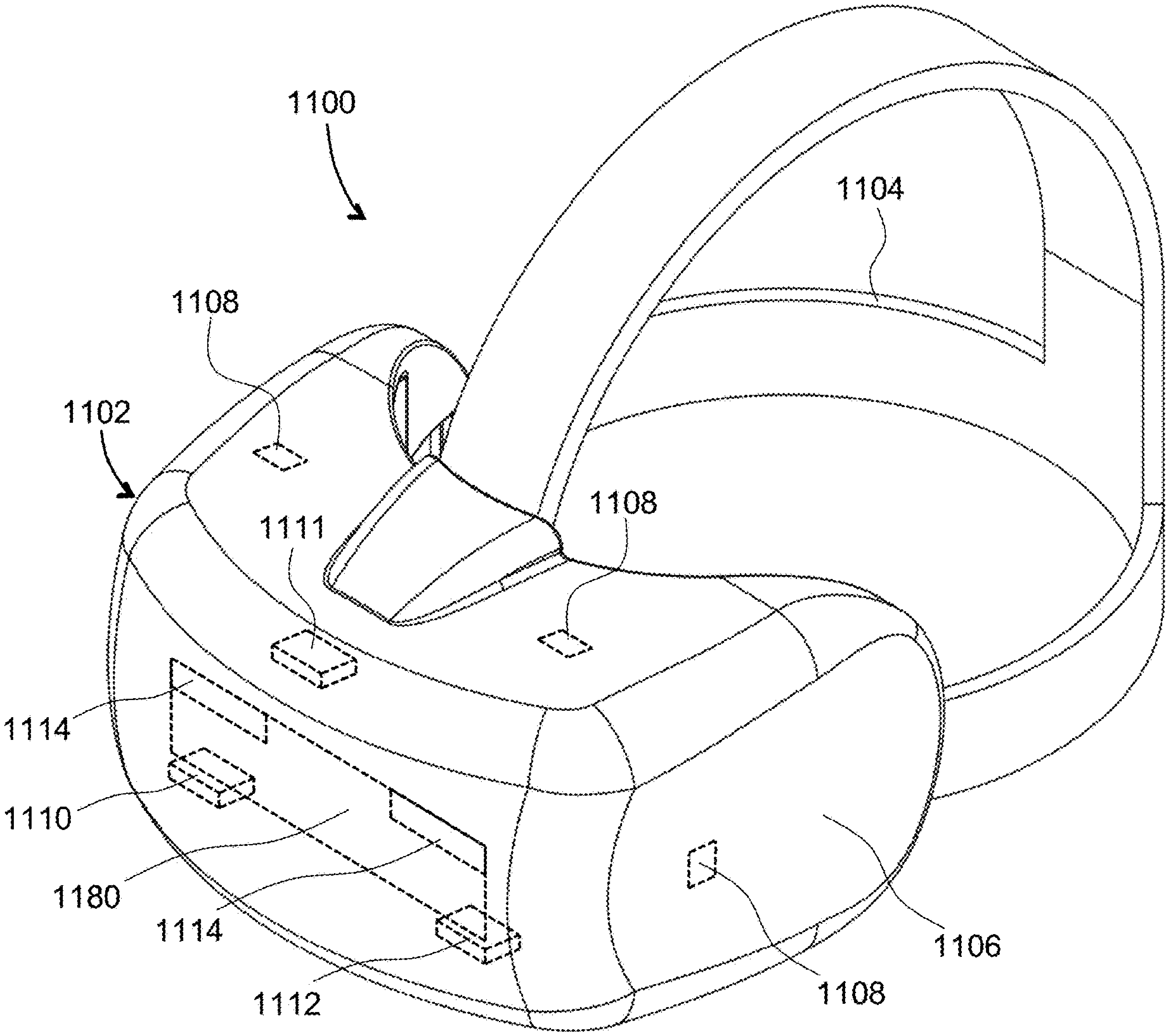


FIG. 10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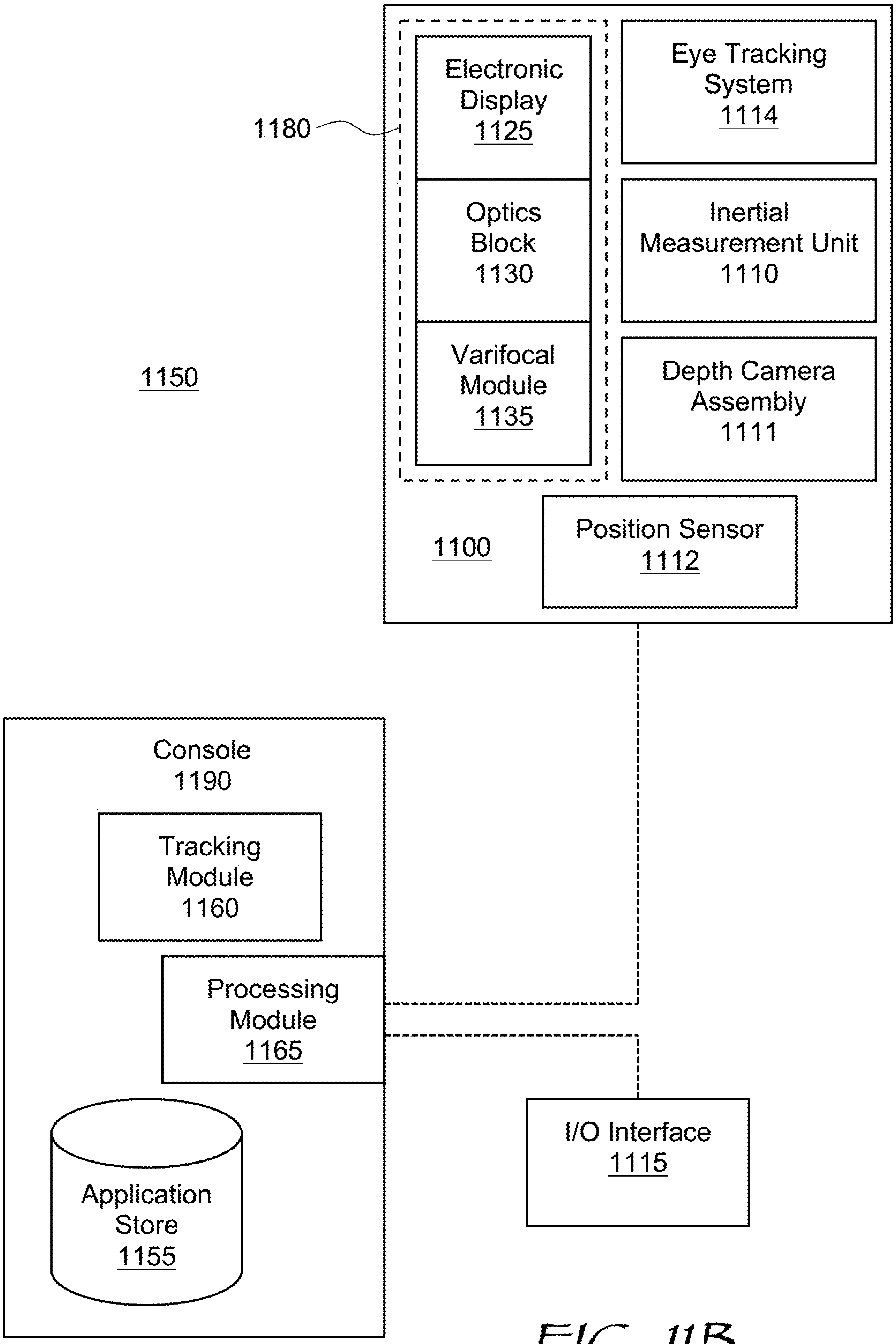
1106

FIG. 11A


Electronic Display 1125
1180
Optics Block 1130
Varifocal Module 1135
Eye Tracking System 1114
Inertial Measurement Unit 1110
Depth Camera Assembly 1111
1150
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Position Sensor 1112
Console 1190
Tracking Module 1160
Processing Module 1165
Application Store 1155
I/O Interface 1115

FIG. 11B

LOW-OBLIQUITY PUPIL RELAY FOR TILTABLE REFLECTORS

TECHNICAL FIELD

The present disclosure relates to wearable headsets, and in particular to components and modules for wearable visual display headsets.

BACKGROUND

Head mounted displays (HMD), helmet mounted displays, near-eye displays (NED), and the like are being used increasingly for displaying virtual reality (VR) content, augmented reality (AR) content, mixed reality (MR) content, etc. Such displays are finding applications in diverse fields including entertainment, education, training and biomedical science, to name just a few examples. The displayed VR/AR/MR content can be three-dimensional (3D) by providing individual images to each eye of the user. Eye position and gaze direction, and/or orientation of the user may be tracked in real time, and the displayed imagery may be dynamically adjusted depending on the user's head orientation and gaze direction, to match virtual objects to real objects observed by the user, and generally to provide an experience of immersion into a simulated or augmented environment.

Compact display devices are desired for head-mounted displays. Because a display of HMD or NED is usually worn on the head of a user, a large, bulky, unbalanced, and/or heavy display device would be cumbersome and may be uncomfortable for the user to wear.

Projector-based displays provide images in angular domain, which can be observed by a user directly, without an intermediate screen or a display panel. A waveguide may be used to carry the image in angular domain to the user's eye. The lack of a screen or high numerical aperture collimating optics in a scanning projector display enables size and weight reduction of the display. A scanner for a projector display needs to be fast, have a wide scanning range, and preserve the optical quality of the beam being scanned to form an image in angular domain.

BRIEF DESCRIPTION OF THE DRAWINGS

Exemplary embodiments will now be described in conjunction with the drawings, in which:

FIG. **1** is a schematic view of a beam scanner including a beam scanner including a pupil relay between tiltable reflectors, in accordance with the present disclosure;

FIGS. **2**A and **2**B are a schematic ray-traced side views of a near-eye display including the beam scanner of FIG. **1**;

FIG. **2**C is a ray-traced three-dimensional view of the near-eye display of FIGS. **2**A and **2**B;

FIG. **2**D is a ray-traced cross-sectional view of a curved reflector embodiment with chromatic aberration compensation;

FIG. **3**A is a schematic view of a variant of the beam scanner of this disclosure including a buried mirror;

FIG. **3**B is a ray-trace diagram of the beam scanner of FIG. **3**A;

FIG. **4**A is a schematic cross-sectional view of a polarization volume hologram (PVH) grating usable in the near-eye displays of FIGS. **2**A-**2**C and FIG. **3**;

FIG. **4**B is a schematic diagram illustrating the principle of operation of the PVH grating of FIG. **4**A;

FIGS. **5**A and **5**B are a schematic view and a raytrace diagram, respectively, of a variant of the beam scanner of this disclosure including a second polarization beamsplitter;

FIGS. **6**A and **6**B are a schematic view and a raytrace diagram, respectively, of a variant of the beam scanner of this disclosure including a curved reflector, a secondary reflector, and a tiltable reflector;

FIGS. **7**A and **7**B are a schematic view and a raytrace diagram, respectively, of a variant of the beam scanner of this disclosure including a collimating lens assembly;

FIGS. **8**A, **8**B, and **8**C are frontal views of multi-emitter light sources usable in near-eye displays disclosed herein;

FIG. **9**A is a graph of aspect ratio of a field of view (FOV) of a scanning projector display as a function of beam obliquity;

FIG. **9**B is a schematic view of a FOV at zero obliquity in FIG. **9**A;

FIG. **9**C is a schematic view of a FOV at maximum obliquity in FIG. **9**A;

FIG. **10** is a block diagram of a near-eye display with a floating FOV;

FIG. **11**A is an isometric view of a head-mounted display of the present disclosure; and

FIG. **11**B is a block diagram of a virtual reality system including the headset of FIG. **11**A.

DETAILED DESCRIPTION

While the present teachings are described in conjunction with various embodiments and examples, it is not intended that the present teachings be limited to such embodiments. On the contrary, the present teachings encompass various alternatives and equivalents, as will be appreciated by those of skill in the art. All statements herein reciting principles, aspects, and embodiments of this disclosure, as well as specific examples thereof, are intended to encompass both structural and functional equivalents thereof. Additionally, it is intended that such equivalents include both currently known equivalents as well as equivalents developed in the future, i.e., any elements developed that perform the same function, regardless of structure.

As used herein, the terms "first", "second", and so forth are not intended to imply sequential ordering, but rather are intended to distinguish one element from another, unless explicitly stated. Similarly, sequential ordering of method steps does not imply a sequential order of their execution, unless explicitly stated. In FIGS. **1**, **2**A, **2**B, **2**C, **3**A, **3**B, **5**A, **5**B, **6**A, **6**B, **7**A, **7**B, and FIG. **10**, similar reference numerals denote similar elements.

One or more tiltable reflectors may be used to scan a light beam emitted by a light source to form an image in angular domain for observation by a user of a near-eye display. As the light beam is scanned by the tiltable reflector(s), the brightness and/or color of the scanned light beam are varied in coordination with the scanning, in accordance with corresponding pixels of the image to be displayed. The entire image is formed when the light beam is scanned in two dimensions, e.g. over X- and Y-viewing angles, over the entire frame or field of view (FOV) of the display. When the frame rate is high enough, the eye integrates the scanned light beam, enabling the user to see the displayed imagery substantially without flicker.

One challenge associated with some near-eye display image scanners is reduction of field of view (FOV) caused by an oblique angle of incidence of the light beam onto a tiltable reflector of the beam scanner. The oblique angle may be required by the optical geometry used, e.g. to physically separate an impinging light beam from the scanned, i.e. reflected, light beam. The FOV reduction is caused by distortion of the solid angle representing the range of scanning at oblique angles of incidence of light beam at the tiltable reflector.

A scanned light beam may be coupled to an input grating of a pupil-replicating waveguide. The function of the input grating is to couple the impinging light beam to propagate in the waveguide, e.g. by total internal reflection (TIR). Another challenge associated with some near-eye display image scanners is that the light beam shifts along the input grating as it is scanned, which requires the size of the input grating to be increased to capture the scanned light beam at the extreme scanning angles. Light redirected by a large input grating may impinge on the input grating several times as it propagates by TIR inside the waveguide, causing brightness and power loss and worsening a modulation transfer function (MTF) of the image being displayed to the user.

In most scanning displays, the scanning needs to be performed about two non-parallel axes of scanning. A single 2D tiltable reflector may be used for this purpose. Alternatively, two 1D tiltable reflectors may be used. Although this may simplify the scanner construction, the optics required to couple two tiltable reflectors may be comparatively large and complex.

In accordance with the present disclosure, a pupil relay may be used to couple two tiltable reflectors, as well as to compensate for the scanned beam travel, such that regardless of the beam angle, the beam always propagates through a same location at an exit pupil of the pupil relay, albeit at different angles. The output light beam of the pupil relay may be spatially separated from the input light beam by polarization. This obviates the need in geometrical separation of the beams by oblique angles of incidence, resulting in a compact configuration providing a nearly straight angle of incidence at the tiltable reflector when the latter is in a center (non-tilted) angular position. Low obliquity of the impinging light beam enables the scanning range to be utilized more efficiently. A reduced beam walk enables one to reduce the size of the input grating of a pupil-replicating waveguide, thus improving the image MTF.

In accordance with the present disclosure, there is provided a beam scanner comprising a first tiltable reflector for reflecting a light beam at a variable angle in a first plane; a second tiltable reflector for reflecting the light beam at a variable angle in a second plane; and a beam-folded pupil relay for receiving the light beam from the first tiltable reflector and relaying the light beam to the second tiltable reflector. The beam-folded pupil relay includes a beamsplitter for receiving the light beam reflected by the first tiltable reflector; and a first curved reflector for receiving the light beam from the beamsplitter, and for reflecting the light beam back towards the beamsplitter. The beam-folded pupil relay is configured to couple the light beam reflected by the first curved reflector to the second tiltable reflector. The first curved reflector may have a radius of curvature substantially equal to an optical path length from the first tiltable reflector to the first curved reflector, and to an optical path length from the second tiltable reflector to the first curved reflector. The first and second tiltable reflectors may each include a tiltable microelectromechanical system (MEMS) reflector.

In embodiments where the beamsplitter comprises a polarization beamsplitter (PBS) configured to reflect light having a first polarization state and to transmit light having a second polarization state orthogonal to the first polarization state, the beam scanner may further include: a first quarter-wave waveplate (QWP) disposed in an optical path between the PBS and the first curved reflector and configured to convert polarization of the light beam upon double pass through the first QWP between the first and second polarization states; and a second QWP disposed in an optical path between the PBS and the second tiltable reflector and configured to convert polarization of the light beam upon double pass through the second QWP between the first and second polarization states.

The beam scanner may further include a second curved reflector and a third QWP. The second curved reflector is configured to receive the light beam from the beamsplitter after reflection from the first and second tiltable reflectors and reflect the light beam to an exit pupil of the beam scanner. The third QWP may be disposed in an optical path between the beamsplitter and the second curved reflector and configured to convert polarization of the light beam propagated therethrough to a circular polarization. In some embodiments, the first curved reflector and the first tiltable reflector are disposed on opposite sides of the beamsplitter, and the second curved reflector and the second tiltable reflector are disposed on opposite sides of the beamsplitter. The beam scanner may further include a first lens in an optical path between the first tiltable reflector and the PBS, for collimating the light beam impinging onto the first tiltable reflector, and a second lens in an optical path between the second tiltable reflector and the PBS, for collimating the light beam impinging onto the second tiltable reflector.

The first and second curved reflectors may each include a meniscus lens having a proximal concave surface and a distal convex surface, and a reflective coating at the distal convex surface. In embodiments where the light beam comprises first and second color channel components, the reflective coating of at least one of the first or second curved reflectors may include a first dichroic coating for reflecting the first color channel component and a second coating for reflecting the second color channel component. The first dichroic coating and the second coating may be disposed at different distances from the proximal concave surface of the meniscus lens.

In accordance with the present disclosure, there is provided a projector comprising a light source for providing a light beam, and any of the beam scanners described above coupled to the light source for receiving the light beam. In embodiments where the first curved reflector and the first tiltable reflector are disposed on opposite sides of the beamsplitter, and where the second curved reflector and the second tiltable reflector are disposed on opposite sides of the beamsplitter, the first curved reflector may include an opening for coupling the light beam from the light source to the beamsplitter.

In accordance with the present disclosure, there is further provided a near-eye display for providing an image in angular domain to an eyebox of the near-eye display. The near-eye display includes a first tiltable reflector for reflecting the light beam at a variable angle in a first plane, a second tiltable reflector for reflecting the light beam at a variable angle in a second plane, and a beam-folded pupil relay described above. The beam-folded pupil relay may be configured for receiving the light beam from the first tiltable reflector and relaying the light beam to the second tiltable reflector. By way of a non-limiting example, the beam-folded pupil relay may include: a beamsplitter for receiving the light beam reflected by the first tiltable reflector; a first curved reflector for receiving the light beam from the beamsplitter, and for reflecting the light beam back towards the beamsplitter, wherein the beam-folded pupil relay is configured to couple the light beam reflected by the first curved reflector to the second tiltable reflector; and a second curved reflector configured to receive the light beam from the beamsplitter after reflection from the first and second tiltable reflectors, and to reflect the light beam to an exit pupil of the beam scanner.

A pupil-replicating waveguide may be provided in the near-eye display. The pupil-replicating waveguide may include a polarization-selective input grating for coupling the light beam into the pupil-replicating waveguide, wherein the polarization-selective input grating is disposed proximate the exit pupil of the beam scanner for receiving the light beam reflected by the second curved reflector. In embodiments where the beamsplitter comprises a PBS configured to reflect light having a first polarization state and to transmit light having a second polarization state orthogonal to the first polarization state, the beam scanner may further include first, second, and third QWPs. The first QWP may be disposed in an optical path between the PBS and the first curved reflector and configured to convert polarization of the light beam upon double pass through the first QWP between the first and second polarization states. The second QWP may be disposed in an optical path between the PBS and the second tiltable reflector and configured to convert polarization of the light beam upon double pass through the second QWP between the first and second polarization states. The third QWP may be disposed in an optical path between the beamsplitter and the second curved reflector and configured to convert polarization of the light beam propagated therethrough to a circular polarization of a first handedness. The polarization-selective input grating may be configured to propagate substantially without diffraction circularly polarized light of the first handedness, and to diffract circularly polarized light of a second handedness opposite to the first handedness. The polarization-selective input grating may include a polarization volume hologram.

In some embodiments, the near-eye display further includes a controller operably coupled to the light source and the first and second tiltable reflectors and configured to: operate the first and second tiltable reflectors to cause the light beam at the exit pupil of the beam-folded pupil relay to have a beam angle corresponding to a pixel of an image to be displayed; and operate the light source in coordination with operating the first and second tiltable reflectors, such that the light beam has brightness corresponding to the pixel of the image to be displayed.

In some embodiments, the first and second tiltable reflectors are both tiltable about two axes. The near-eye display may further include an eye tracker operably coupled to the controller and configured to determine a gaze direction of a user of the near-eye display. The controller may be is further configured to: operate the first tiltable reflector to scan the light beam to form an image in angular domain for displaying to the user; use the eye tracker to determine the gaze direction of the user; and operate the second tiltable reflector to shift a field of view towards the gaze direction of the user.

Various exemplary embodiments of a beam scanner will now be considered. Referring to FIG. **1**, a beam scanner **130** includes a first tiltable reflector **102** for reflecting a light beam **104** provided by a light source **106**. The reflection occurs at a variable angle in a first plane, e.g. in YZ plane (up and down in plane of FIG. **1**). A second tiltable reflector **152** is provided for reflecting the light beam **104** at a variable angle in a second plane, e.g. XY plane (out of plane of FIG. **1**). A beam-folded pupil relay **108** is configured to receive

the light beam **104** from the first tiltable reflector **102** and relay the light beam **104** to the second tiltable reflector **152**.

In the embodiment shown, the beam-folded pupil relay **108** includes a beamsplitter **112** and a first curved reflector **114**. The light source **106** emits the light beam **104**, which may propagate through an opening **115** in the first curved reflector **114**, and through the beamsplitter **112** towards the first tiltable reflector **102**. The beamsplitter **112** is configured to receive the light beam **104** reflected by the first tiltable reflector **102**, and to transmit the light beam **104** back towards the first curved reflector **114**. The first curved reflector **114** is configured to receive the light beam **104** propagated through the beamsplitter **112**, and to reflect the light beam **104** back towards the beamsplitter **112**. In the embodiment shown, the light beam **104** is reflected to propagate back substantially along an optical path of the impinging light beam.

The backward reflection occurs regardless of the angle of tilt of the tiltable reflector **102**. For example, in FIG. **1**, a first reflected beam **104**A (at an upward-tilted tiltable reflector **102**) is reflected by the beamsplitter **112** to propagate back through a first optical path **105**A, and a second reflected beam **104**B (at a downward-tilted tiltable reflector **102**) is at reflected by the beamsplitter **112** to propagate back through a second optical path **105**B. To achieve backreflection, the curved reflector **114** may have a radius of curvature substantially equal to an optical path length from the first tiltable reflector **102** to the first curved reflector **114**. At this condition, the light beam **104** reflected from the tiltable reflector **102** will always propagate along a radius of curvature of the curved reflector **114**, and consequently will always be at a normal (zero) angle of incidence at the curved reflector **114**, and will get retroreflected.

In some embodiments, the opening **115** is disposed off-center w.r.t. the first curved reflector **114**. The shift may be significant enough to place the impinging light beam **104** outside the scanning range of the tiltable reflector **102**. Shifting the opening **115** outside the scanning range of the tiltable reflector **102**, i.e. outside of the FOV of the display, may effectively remove a dimming artifact where the image is dimmer on one area corresponding to the field angle at which the light beam **104** reflected from the first tiltable reflector **102** propagates back through the opening **115**. It is further noted that, if the opening **115** is disposed outside of the display FOV, the first tiltable reflector **102** may need to be pre-tilted.

The beamsplitter **112** is configured to reflect the light beam **104** back-reflected by the curved reflector **114** to the second tiltable reflector **152**. An optical path length from the first reflector **114** to the second tiltable reflector **152** may be also equal to the radius of curvature of the curved reflector **114**. At this condition, the light beam **104** will always be centered on the second tiltable reflector **152**, regardless of the angle of tilt of the first tiltable reflector **102**, as shown. When the two optical paths are equal, the magnification along the optical path from the first tiltable reflector **102** to the second tiltable reflector **152** is equal to unity.

In some embodiments, the two paths are not equal. In other words, the path length between the first curved reflector **114** and the first tiltable reflector **102** may be different from a path length between the first curved reflector **114** and the second tiltable reflector **152**. Thus results in the magnification greater or less than unity. It is noted that the magnification of the pupil results in de-magnification of the scanning range, and vice versa.

To preserve optical power of the light beam **104**, the light source **106** of the beam scanner **130** may be constructed to emit polarized light, and the beamsplitter **112** may be made polarization-selective, i.e. configured to reflect light having a first polarization state and to transmit light having a second polarization state orthogonal to the first polarization state. The polarization state of the light beam **104** may be manipulated by using polarization-converting optical elements such as waveplates to ensure the desired folded beam path. For example, a first quarter-wave waveplate (QWP) **121** may be disposed in an optical path between the beamsplitter **112** and the first curved reflector **114** and configured to convert polarization of the light beam **104** upon double pass through the first QWP **121** between the first and second polarization states. This will ensure that the light beam **104** will not repeat its path through the beamsplitter **112**, i.e. if the light beam transmitted through the beamsplitter **112** on the first pass, e.g. before impinging onto the first curved reflector **114**, the light beam **104** will be reflected by the beamsplitter **112** on the second pass towards the second tiltable reflector **152**, and vice versa.

A second QWP **122** may be disposed in an optical path between the beamsplitter **112** and the second tiltable reflector **152** and configured to convert polarization of the light beam upon double pass through the second QWP**122** between the first and second polarization states. Again, this will ensure that the light beam **104** will not repeat its path through the beamsplitter **112**, i.e. if the light beam **104** was reflected by the PBS **122** towards the second tiltable reflector **152** on the first pass, it will then propagate through the PBS **122** on the second pass, i.e. upwards in FIG. **1**, as shown.

In some embodiments, the beam scanner **130** further includes a second curved reflector **164** configured to receive the light beam **104** from the beamsplitter **112** after reflecting from the first **102** and second **152** tiltable reflectors as described above. The second curved reflector **164** and the second tiltable reflector **152** are disposed on opposite sides of the beamsplitter **112**; and, for that matter, the first curved reflector **114** and the first tiltable reflector **102** are also disposed on opposite sides of the beamsplitter, resulting in a compact overall configuration. In operation, the second curved reflector **164** reflects the light beam **104** to an exit pupil **110** of the beam scanner **130**.

A receiving optical device, such as a pupil-replicating waveguide **140**, may be disposed at or proximate the exit pupil **110** for receiving the light beam **104**. The pupil-replicating waveguide **140** may include a polarization-selective element sensitive to handedness of circular polarization of light. A third QWP **123** may be disposed in an optical path between the beamsplitter **112** and the second curved reflector **164** and configured to convert polarization of the light beam propagated therethrough to a circular polarization of a handedness that causes the light beam **104** to propagate through the pupil-replicating waveguide **140**. Upon reflecting from the second curved reflector **164**, the handedness of the circularly polarized light beam **104** will change to an opposite handedness, causing the polarization-selective element to redirect the light beam for propagation in the pupil-replicating waveguide **140**. It is noted that the polarization-selective element may be sensitive to circular polarization, linear polarization, and generally to any two orthogonal states of polarization.

FIGS. **2**A, **2**B, and **2**C show a near-eye display **200** including a pupil-replicating waveguide assembly **240** optically coupled to a beam scanner **230** configured to receive a light beam **204** from a light source **206**. The pupil-replicating waveguide assembly **240** may have one, two, three or more waveguides. Two waveguides, **240-1** and **240-2**, are shown as an example. The beam scanner **230** includes first **202** and second **252** tiltable reflectors optically coupled to each other via a beam-folded pupil relay **208**, which is similar to the beam-folded pupil relay **108** of FIG. **1**. The first **202** and second **252** tiltable reflectors (FIG. **2**A) may be microelectromechanical (MEMS) 1D or 2D tiltable reflectors, and may be disposed in hermetic packages having transparent windows **203** and **253**, respectively. A controller **290** may be operably coupled to the first **202** and second **252** tiltable reflectors and the light source **206**.

The beam-folded pupil relay **208** includes a polarization beamsplitter (PBS) **212** and first **214** and second **264** curved reflectors, each of which in this embodiment includes a meniscus lens having a reflective coating on its distal (i.e. farthest form the PBS **212**) convex surface. The PBS **212** is configured to reflect light having a first polarization state polarized perpendicular to the plane of FIG. **2** (i.e. XZ plane), and to transmit light having a second polarization state polarized in plane of FIG. **2** (i.e. YZ plane) in this example. The second polarization state is orthogonal to the first polarization state.

Similarly to the beam-folding relay **108** of FIG. **1**, the beam-folded pupil relay **208** of FIG. **2**A may further include first **221** and second **222** QWPs. The first QWP **221** is disposed in an optical path between the PBS **212** and the first curved reflector **214**. The first QWP **221** may be oriented such that a polarization state of a light beam changes to an orthogonal polarization state upon double passing the first QWP **221**, i.e. from the first polarization state to the second polarization state, and from the second polarization state to the first polarization state. The second QWP **222** is disposed in an optical path between the second tiltable reflector **252** and the PBS **212**, and may also be oriented to convert between two orthogonal polarization states upon double pass. A first lens **231** may be disposed in an optical path between the first tiltable reflector **212** and the PBS **212**, for collimating the impinging diverging light beam **204**, as well as for focusing the light beam **204** reflected by the first tiltable reflector **202** to propagate towards the PBS **212**. A second lens **232** may be disposed in an optical path between the PBS **212** and the second tiltable reflector **252**, for collimating the impinging diverging light beam **204**, as well as for focusing the light beam **204** reflected by the second tiltable reflector **252** to propagate towards the PBS **212**.

In operation, the light source **206** emits the light beam **204**, which has a circular polarization in this example. Upon a first propagation through the first QWP **221**, the light beam **204** is in the second polarization state, which is in YZ plane in this example. Since the light beam **204** is in the second polarization state, it propagates through the PBS **212** substantially without a reflection loss. Then, the light beam **204** is reflected by the first tiltable reflector **202** and is reflected back to the first curved reflector **214**, thus propagating through the first QWP **221** again. The first curved reflector **214** reflects the light beam again through the first QWP **221**, which changes the polarization state of the light beam **204** to the first polarization state, i.e. linearly polarized in XY plane, and is reflected by the PBS **212** towards the second tiltable reflector **252**. Upon double passing the second QWP **222**, the light beam **204** becomes linearly polarized in YZ plane again (second polarization state and propagates through the PBS **212**. A third QWP **223** makes the propagating light beam **204** circularly polarized at a first handedness of circular polarization.

In the embodiment shown, the waveguide assembly **240** of the near-eye display **200** includes two pupil-replicating waveguides, **240-1** and **240-2**. At least one pupil-replicating waveguide may be provided. Each pupil-replicating waveguide **240-1** and **240-2** includes a polarization-selective input grating **260**, which is configured to propagate the circularly polarized light beam **204** of the first handedness. Then, the light beam **204** is reflected back by the second curved reflector **264**, towards an exit pupil **210** located between the polarization-selective input gratings **260** of the pupil-replicating waveguides **240-1** and **240-2**. Upon reflection from the second curved reflector **264**, the handedness of circular polarization of the light beam **204** changes to the opposite handedness, and the polarization-selective input gratings **260** redirect the light beam **204** to propagate in the pupil-replicating waveguides **240-1** and **240-2**.

In some beam scanners disclosed herein, the order of light propagation in the pupil relay may be reversed, such that the light propagates from the second to the first tiltable reflector. Referring back to FIG. **1** for example, the polarization of the light beam **104** emitted by the light source **106**, and the orientation of the first QWP **121** may be selected to cause the light beam **104** to be reflected by the beamsplitter **112** towards the second tiltable reflector **152**. In that case, the second QWP **122** may be moved to the location **122*** in front of the first tiltable reflector **102**. That causes the light beam reflected by the second tiltable reflector **102** to be reflected by the beamsplitter **112** back to the first curved reflector **102**, and, after two more passes through the first QWP **121**, to be transmitted by the beamsplitter **112** to propagate to the first tiltable reflector **102**.

Referring back to FIGS. **2**A and **2**B, the first **202** and second **252** tiltable reflectors may each include a MEMS tiltable reflector. Each MEMS reflector may be tiltable in one dimension, e.g. one MEMS reflector tiltable up-down and the other MEMS reflector tiltable left-right, or in two dimensions, e.g. both up and down and left-right in FIG. **2**, i.e. in-plane and out-of-plane of FIG. **2**. This may be useful in some embodiments considered further below. The first **231** and second **232** lenses, as well as the meniscus reflective lenses of the first **214** and second **264** curved reflector, may be optimized to reduce optical aberrations across the entire range of scanning of the tiltable reflector **202**. Another lens **265** may be provided on the third QWP **223** to balance focusing and/or aberrations in the system. The propagation of the light beam **204** is further illustrated in FIGS. **2**B and **2**C, which show that the light source **206** emits a converging light beam propagating through a center opening **215** in the first curved reflector **214**.

In embodiments where the light beam includes color channel components, e.g. red (R), green (G), and blue (B) color channel components, the first **214** curved reflector may be optimized to lessen the effects of chromatic aberration. Referring to FIG. **2**D, the light beam **204** includes a R channel component **204**R, a G channel component **204**G, and a B channel component **204**B. The first curved reflector **214** includes a distal convex reflector surface **284** (top portion of FIG. **2**D) and a proximal concave refractive surface **285**. Herein, the terms "distal" and "proximal" are with reference to the PBS **212**. As illustrated at the bottom portion of FIG. **2**D, the convex reflector surface **284** may include a plurality of dichroic coatings each reflecting its own color channel component and optionally transmitting other channel components. For example, a B channel dichroic coating **284**B may reflect B channel component while transmitting R and G channel components; a G channel dichroic coating **284**G may reflect G channel component while transmitting R channel component; and an R channel coating **284**R may reflect the R channel component. The R channel coating **284**R may, but does not have to be, dichroic, as it reflects all remaining light. The R, G, and B channel coatings **284**R, **284**G, and **284**B may be disposed at different distances from the proximal concave refractive surface **285** of the first curved reflector **214** to offset or lessen chromatic aberration that may be present in the near-eye display **200**. The order of the R, G, and B channel coatings **284**R, **284**G, and **284**B may differ from the one illustrated. Chromatic aberration may be mitigated by other means, as well. For example, the source points of the R, G, and B channel light sources of the light source **206** may be spatially separated along the direction of propagation to pre-compensate for the chromatic effects. In another example, the first lens **231** and/or the second lens **232** may be achromatized, i.e. by using a combination of optical materials with different dispersion properties, as well as diffractive optical elements.

The second curved reflector **264** may be constructed in a similar manner. At least two coatings may be provided for the first **214** and/or second **264** curved reflectors. One of the spaced apart coatings, or both coatings, may be dichroic. Three or more coatings, some of them dichroic, may be provided to better offset the chromatic aberration.

The controller **290** of the near-eye display **200** (FIG. **2**A) may be configured to operate the first **202** and second **252** tiltable reflectors to cause the light beam **204** at the exit pupil **210** of the beam-folded pupil relay **208** to have a beam angle corresponding to a particular pixel of an image in angular domain to be displayed by the near-eye display **200**. The controller **290** operates the light source **206** in coordination with operating the tiltable reflectors **202** and **252**, such that the light beam **204** has brightness, color, etc. corresponding to the pixel(s) being displayed. The entire image in angular domain is formed when the light beam **204** is scanned in two dimensions, e.g. over X- and Y-viewing angles, over the entire frame or field of view (FOV) of the near-eye display **200**. When the frame rate is high enough, the eye of the user integrates the scanned light beam **204**, enabling the user to see the displayed imagery substantially without flicker.

Referring now to FIGS. **3**A and **3**B, a beam scanner **330** may utilize a polarization-selective input coupler coupling one polarization of light and transmitting the other, orthogonal polarization of light, e.g. coupling circularly polarized light of one handedness only. The beam scanner **330** includes a 2D tiltable reflector **302**, a QWP **303**, a buried polarization-selective reflector **370** buried in a transparent slab **372**, first **331** and second **332** lenses, and a curved reflector **364**. In operation, a linearly polarized light beam **304** from a light source **306** propagates in the transparent slab **372** and is reflected by the buried polarization-selective reflector **370** to impinge onto the tiltable reflector **302** through the first lens **331** and the QWP **303**. The first lens **331** collimates the light beam **304**. The tiltable reflector **302** reflects the light beam **304** at a variable angle. Upon double propagation through the QWP **303**, the light beam changes polarization to an orthogonal linear polarization, and consequently propagates through the buried polarization-selective reflector **370**. The first lens **331** focuses the light beam **304** (FIG. **3**B) to propagate towards the second lens **332**. The second lens **332** relays the light beam **304** to the curved reflector **364** through the waveguide assembly **340**, which may include one or more waveguides equipped with a polarization-selective input coupler mentioned above. A QWP **303*** may be provided to convert linear polarization of the light beam **304** into a circular polarization, for use with a circular polarization selective coupler. The curved reflector **364** directs the light beam **304** to an exit pupil **310**. Upon reflection from the curved reflector **364**, the light beam **304** changes the handedness of the circular polarization, and the polarization-selective input coupler(s) of the waveguide assembly **340** may now couple the light beam **304** into the pupil-replicating waveguide(s) of the waveguide assembly **340**.

An exemplary embodiment of the polarization-selective couplers, such as the polarization-selective input grating **260** (FIG. **2**A), will now be considered. By way of example, referring to FIG. **4**A, a polarization volume hologram (PVH) grating **400** includes an LC layer **404** bound by opposed top **405** and bottom **406** parallel surfaces. The LC layer **404** may include an LC fluid containing rod-like LC molecules **407** with positive dielectric anisotropy, e.g. nematic LC molecules. A chiral dopant may be added to the LC fluid, causing the LC molecules in the LC fluid to self-organize into a periodic helical configuration including helical structures **408** extending between the top **405** and bottom **406** parallel surfaces of the LC layer **404**. Such a configuration of the LC molecules **407**, termed herein a cholesteric configuration, includes a plurality of helical periods p, e.g. at least two, at least five, at least ten, at least twenty, or at least fifty helical periods p between the top **405** and bottom **406** parallel surfaces of the LC layer **404**. Boundary LC molecules **407***b* at the top surface **405** of the LC layer **404** may be oriented at an angle to the top surface **405**. The boundary LC molecules **407***b* may have a spatially varying azimuthal angle, e.g. linearly varying along X-axis parallel to the top surface **405**, as shown in FIG. **4**A. To that end, an alignment layer **412** may be provided at the top surface **405** of the LC layer **404**. The alignment layer **412** may be configured to provide the desired orientation pattern of the boundary LC molecules **407***b*, such as the linear dependence of the azimuthal angle on the X-coordinate. A pattern of spatially varying polarization directions of the UV light may be selected to match a desired orientation pattern of the boundary LC molecules **407***a* at the top surface **405** and/or the bottom surface **406** of the LC layer **404**. When the alignment layer **412** is coated with the cholesteric LC fluid, the boundary LC molecules **407***a* are oriented along the photopolymerized chains of the alignment layer **412**, thus adopting the desired surface orientation pattern. Adjacent LC molecules adopt helical patterns extending from the top **405** to the bottom **406** surfaces of the LC layer **404**, as shown.

The boundary LC molecules **407***b* define relative phases of the helical structures **408** having the helical period p. The helical structures **408** form a volume grating comprising helical fringes **414** tilted at an angle ϕ, as shown in FIG. **4**A. The steepness of the tilt angle ϕ depends on the rate of variation of the azimuthal angle of the boundary LC molecules **407***b* at the top surface **405** and p. Thus, the tilt angle ϕ is determined by the surface alignment pattern of the boundary LC molecules **407**A at the alignment layer **412**. The volume grating has a period Λ_x along X-axis and Λ_y along Y-axis. In some embodiments, the periodic helical structures **408** of the LC molecules **407** may be polymer-stabilized by mixing in a stabilizing polymer into the LC fluid, and curing (polymerizing) the stabilizing polymer.

The helical nature of the fringes **414** of the volume grating makes the PVH grating **400** preferably responsive to light of polarization having one particular handedness, e.g. left- or right-circular polarization, while being substantially non-responsive to light of the opposite handedness of polarization. Thus, the helical fringes **414** make the PVH grating **400** polarization-selective, causing the PVH grating **400** to diffract light of only one handedness of circular polarization. This is illustrated in FIG. **4**B, which shows a light beam **420** impinging onto the PVH grating **400**. The light beam **420** includes a left circular polarized (LCP) beam component **421** and a right circular polarized (RCP) beam component **422**. The LCP beam component **421** propagates through the PVH grating **400** substantially without diffraction. Herein, the term “substantially without diffraction” means that, even though an insignificant portion of the beam (the LCP beam component **421** in this case) might diffract, the portion of the diffracted light energy is so small that it does not impact the intended performance of the PVH grating **400**. The RCP beam component **422** of the light beam **420** undergoes diffraction, producing a diffracted beam **422'**. The polarization selectivity of the PVH grating **400** results from the effective refractive index of the grating being dependent on the relationship between the handedness, or chirality, of the impinging light beam and the handedness, or chirality, of the grating fringes **414**. It is further noted that the sensitivity of the PVH **400** to right circular polarized light in particular is only meant as an illustrative example. When handedness of the helical fringes **414** is reversed, the PVH **400** may be made sensitive to left circular polarized light.

Referring to FIGS. **5**A and **5**B, a near-eye display **500** includes a pupil-replicating waveguide assembly **540** optically coupled to a beam scanner **530** configured to scan a light beam **504** received from a light source **506**. The pupil-replicating waveguide assembly **540** may have one, two, three or more waveguides. Two waveguides, **540-1** and **540-2**, are shown as an illustrative example. The beam scanner **530** includes first **502** and second **552** tiltable reflectors, e.g. MEMS reflectors having first **503** and second **553** protective windows, respectively. The first **502** and second **552** tiltable reflectors are optically coupled to each other by a beam-folded pupil relay **508** including a first PBS **512**, a first curved reflector **514**, and first **531**, second **532**, and third **533** lenses. The construction and operation of the beam-folded pupil relay **508** is similar to those of the beam-folded pupil relay **108** of FIG. **1** and the beam-folded pupil relay **208** of FIGS. **2**A-**2**C described above. First and second QWPs are not shown in FIGS. **5**A and **5**B for brevity.

The beam-folded pupil relay **508** (FIGS. **5**A and **5**B) further includes a second PBS **562**, which receives the light beam **504** from the first PBS **512** and reflects the light beam **504** towards a second curved reflector **564**. A polarization-flipping QWP **523** changes the polarization state of the light beam **504** after double-pass propagation, causing the reflected light beam **504** to propagate through the second PBS **562** and impinge onto the waveguide assembly **540**. Similarly to the beam scanner **130** of FIG. **1** and to the beam scanner **230** of FIGS. **2**A-**2**C, the light beam **504** may propagate through an opening **515** in the first curved reflector **514**.

In some embodiments, the light source **506** may be disposed to the left of the second PBS **562** in FIGS. **5**A and **5**B, i.e. it may be coupled to the second PBS **562**. The light source **506** may be configured to emit linearly polarized light, which propagates in sequence through the second PBS **562**, the first PBS **512**, and impinges onto the second tiltable reflector **552**. In some embodiments, the light source **506** may be placed below the second curved reflector **564**, which may be equipped with a small opening, not shown, to propagate the light beam **504** therethrough. The light source **506** may be configured to emit circularly polarized light. After propagating through the polarization-flipping QWP **523** it may be reflected in sequence by the second PBS **562**, the first PBS **512**, and may impinge onto the first tiltable reflector **502**.

Referring to FIGS. **6**A and **6**B, a near-eye display **600** includes a pupil-replicating waveguide assembly **640** optically coupled to a beam scanner **630** configured to receive a light beam **604** from a light source **606**. The pupil-replicating waveguide assembly **640** may have one, two, three or more waveguides. Two waveguides are shown as an example. The beam scanner **630** includes a 2D tiltable reflector **602**, e.g. a MEMS tiltable reflector having a window **603** for hermetic packaging the MEMS tiltable reflector, optically coupled to an exit pupil **610** by a beam-folded pupil relay **608** including a PBS **612**, a curved reflector **614**, and first **631** and second **632** lenses. The beam-folded pupil relay **608** (FIGS. **6**A and **6**B) further includes a secondary reflector **670**. In operation, the secondary reflector **670** receives the light beam **604** from the light source **606** and reflects the light beam **604** towards the tiltable reflector **602** through the first lens **631**, which collimates the light beam **604**. The reflected light beam **604** propagates past the secondary reflector **670** (because the light beam **604** is broader than the secondary reflector **670** at that location), propagates through the second lens **632**, and is reflected by the PBS **612** towards the curved reflector **614** through a QWP **621**. The light beam **604** reflected from the curved reflector **614** propagates through the QWP **621** twice and thus changes its polarization state to an orthogonal polarization state, propagating through the PBS **612** and impinging onto the waveguide assembly **640**. In some embodiments, the secondary reflector **670** may be made polarization-selective, and a QWP may be provided in place of the window **603** to flip polarization of the light beam **604** propagated twice through the QWP such that upon a subsequent propagation, the light beam **604** is transmitted through the secondary reflector **670**, thereby avoiding the optical losses at the reflector **670**. Alternatively, the light source **606** may be placed to the left of the PBS **612** in FIGS. **6**A and **6**B and be configured to emit the linearly polarized light beam **604** at a linear polarization orientation enabling propagation of the light beam **604** through the PBS **612**. Then, upon double-pass propagation through the QWP in place of the window **603**, the light beam **604** becomes orthogonally polarized and is reflected by the PBS **612** towards the curved reflector **614**. Alternatively, the light source **606** may be disposed under the curved reflector **614**. In this embodiment, the light source **606** may be configured to emit circularly polarized light, such that the light beam **604** becomes linearly polarized after propagating through the QWP **621** and is reflected by the PBS **612** towards the tiltable reflector **602**.

Referring to FIGS. **7**A and **7**B, a near-eye display **700** includes a pupil-replicating waveguide assembly **740** optically coupled to a beam scanner **730** configured to receive a light beam **704** from a light source **706**. The pupil-replicating waveguide assembly **740** may have one, two, three or more waveguides. The beam scanner **730** includes a 2D tiltable reflector **702**, e.g. a MEMS tiltable reflector, optically coupled to an exit pupil **710** by a beam-folded pupil relay **708** including a PBS **712**, a curved reflector **714**, and a lens assembly **780** including first **731**, second **732**, and third **733** lenses. The beam-folded pupil relay **708** (FIGS. **7**A and **7**B) further includes first **721** and second **722** QWPs. In operation, the PBS **712** receives the light beam **704** from the light source **706** and reflects the light beam **704** towards the tiltable reflector **702** through the QWP **721** and an optional auxiliary lens **734**. The reflected light beam **704** propagates again through the first QWP **621** and the auxiliary lens **734**, propagates through the PBS **712** (since its polarization has been flipped by double-pass propagation through the first QWP **721**), through the second QWP **722**, and impinges onto the curved reflector **714**. Upon reflection from the curved reflector **714**, the light beam **704** flips the polarization again, is reflected by the PBS **712** towards the lens assembly **780**, which collimates the light beam **704** at the waveguide assembly **740**.

In some embodiments, the light source **706** may be disposed to the right of the curved reflector **714** in FIGS. **7**A and **7**B and configured to emit the circularly polarized light bam **704**. In operation, the light beam **704** propagates through an opening, not shown, in the curved reflector **714**, propagates through the second QWP **722**, becomes linearly polarized, and is transmitted through the PBS **712**. In this embodiment, the first QWP **721** may be omitted to enable the light beam **704** reflected by the tiltable reflector **702** to propagate again through the PBS **712** towards the curved reflector **714**.

The light sources **106** of FIG. **1**, **206** of FIGS. **2**A and **2**B, **306** of FIG. **3**, **506** of FIGS. **5**A and **5**B, **606** of FIGS. **6**A and **6**B, and **706** of FIGS. **7**A and **7**B may each include a plurality of individually controllable emitters, e.g. superluminescent light-emitting diodes (SLEDs). Several emitters may be provided for each color channel. Referring to FIGS. **8**A, **8**B, and **8**C, four red emitters **800**R may be provided for red (R) color channel (dark-shaded circles); four green emitters **800**G may be provided for green (G) color channel (medium-shaded circles); and four blue emitters **800**B may be provided for blue (B) color channel (light-shaded circles). The emitters **800**R, **800**G, and **800**B may each be ridge emitters sharing a common semiconductor substrate. The emitters **800**R, **800**G, and **800**B may be disposed in a line pattern (FIG. **8**A); in a zigzag pattern (FIG. **8**B); or in a honeycomb pattern (FIG. **8**C), to name just a few examples.

Having a plurality of emitters illuminating a same tiltable reflector enables the scanning of the light beams generated by the emitters to be performed together as a group. When a light source includes a plurality of individual emitters, the illuminating light beam includes a plurality of sub-beams co-propagating at a slight angle w.r.t each other. Maximum angular cone of the sub-beams may be less than 5 degrees, or less than 2 degrees, or less than 1 degree in some embodiments. Multiple emitters and, in some cases, multiple light sources may be used to provide redundancy in case some of light sources fail, increase image resolution, increase overall image brightness, etc. Multiple light sources may each be equipped with its own collimator.

The near-eye displays **200** of FIG. **2**, **300** of FIGS. **3**A-3C, **500** of FIGS. **5**A and **5**B, **600** of FIGS. **6**A and **6**B, and **700** of FIGS. **7**A and **7**B provide a low-obliquity coupling of light beam(s) to a tiltable reflector. Herein, the term “low obliquity” means a low angle of incidence, i.e. a normal incidence, at the tiltable reflector when in a nominal, e.g. a center or zero, angle of tilt. One advantage of having low obliquity is illustrated in FIGS. **9**A to **9**C. Referring first to FIG. **9**A, an aspect ratio of a FOV of a projector using a tiltable reflector is plotted as a function of obliquity, i.e. angle of incidence at the tiltable reflector when in nominal or center position. The aspect ratio is plotted for four cases: 75 degrees by 50 degrees on-axis FOV; 60 degrees by 40 degrees on-axis FOV; 45 degrees by 30 degrees on-axis FOV; and 30 degrees by 20 degrees on-axis FOV. The aspect ratio drops from 1.5 at zero obliquity, i.e. normal incidence, to about 1.1 at 40 degrees obliquity angle.

FIG. **9**B shows a zero-obliquity scanning angular area **900**B and an associated inscribed rectangular FOV **902**B. The zero-obliquity FOV **902**B solid angle is covering most of the angular area **900**B. By comparison, FIG. **9**C shows a 40 degrees obliquity scanning angular area **900**C and an associated inscribed rectangular FOV **902**C. The FOV **902**C solid angle occupies a smaller percentage of the angular area **900**C, and is almost 2 times less than the zero-obliquity FOV **902**B, and has a different aspect ratio. Thus, the low-obliquity coupling improves the utilization of the scanning range of the tiltable reflector, enabling wider fields of view at the same scanning range of the tiltable reflector.

Turning to FIG. **10**, a near-eye display **1000** includes a light source **1006**, a beam scanner **1030** coupled to the light source **1006**, and a pupil-replicating waveguide assembly **1040** coupled to the beam scanner **1030**. The beam scanner **1030** may include any of the beam scanners described herein, e.g. the beam scanner **130** of FIG. **1**, the beam scanner **230** of FIGS. **2**A-**2**C, the beam scanner **330** of FIG. **3**, the beam scanner **530** of FIG. **5**, the beam scanner **630** of FIGS. **6**A and **6**B, and/or the beam scanner **730** of FIGS. **7**A and **7**B. In the embodiment shown, the beam scanner **1030** includes first **1002** and second **1052** tiltable reflectors, e.g. MEMS reflectors tiltable about one or two axes. A controller **1090** is operably coupled to the light source **1006**, the first **1002** and second **1052** tiltable reflectors, and to an optional eye tracker **1088**. The function of the eye tracker **1088** is to determine at least one of position or orientation of a user's eye **1086** in an eyebox **1084**, from which a gaze direction of the user may be determined in real time.

In operation, the controller **1090** operates the first **1002** and second **1052** tiltable reflectors to cause a light beam **1004** at the exit pupil of the beam-folded pupil relay to have a beam angle corresponding to a pixel of an image to be displayed. The light source **1006** is operated by the controller **1090** in coordination with scanning the light beam **1004** to form an image in angular domain for displaying to the user. The pupil-replicating waveguide assembly **1040** ensures that the image may be observed by the user's eye **1086** at any position of the user's eye **1086** in the eyebox **1084**. In some embodiments, the eye tracker **1088** is operated to determine the gaze direction of the user.

In embodiments where each tiltable reflector **1002** and **1052** is a 2D tiltable reflector, one of them, e.g. the first tiltable reflector **1002**, may be operated to scan the light beam **1004** in two non-parallel directions to form the image in angular domain while the other, i.e. the second tiltable reflector **1052** is operated to shift the entire image, i.e. to shift a field of view (FOV) of the near-eye display **1000** towards the gaze direction of the user. The image being rendered by the controller **1090** may be updated accordingly, i.e. shifted in opposite direction by the same amount, to make sure that the virtual image is steady as the FOV is shifted. The resulting effect of "floating" FOV is similar to viewing a dark scenery by using a flashlight, where the flashlight is automatically turned in a direction of user's gaze, illuminating different parts of a surrounding scenery depending where the user is looking at the moment. As the rate of FOV shift is determined by the eye mobility which is generally slower than speed of scanning, the first tiltable reflector **1002** may be made smaller and faster, while the second tiltable reflector **1052** may be made larger and slower.

Referring to FIG. **11**A, an HMD **1100** is an example of an AR/VR wearable display system which encloses the user's face, for a greater degree of immersion into the AR/VR environment. The HMD **1100** is an embodiment of any of the near-eye displays disclosed herein. The function of the HMD **1100** is to augment views of a physical, real-world environment with computer-generated imagery, and/or to generate the entirely virtual 3D imagery. The HMD **1100** may include a front body **1102** and a band **1104**. The front body **1102** is configured for placement in front of eyes of a user in a reliable and comfortable manner, and the band **1104** may be stretched to secure the front body **1102** on the user's head. A display system **1180** may be disposed in the front body **1102** for presenting AR/VR imagery to the user. Sides **1106** of the front body **1102** may be opaque or transparent.

In some embodiments, the front body **1102** includes locators **1108** and an inertial measurement unit (IMU) **1110** for tracking acceleration of the HMD **1100**, and position sensors **1112** for tracking position of the HMD **1100**. The IMU **1110** is an electronic device that generates data indicating a position of the HMD **1100** based on measurement signals received from one or more of position sensors **1112**, which generate one or more measurement signals in response to motion of the HMD **1100**. Examples of position sensors **1112** include: one or more accelerometers, one or more gyroscopes, one or more magnetometers, another suitable type of sensor that detects motion, a type of sensor used for error correction of the IMU **1110**, or some combination thereof. The position sensors **1112** may be located external to the IMU **1110**, internal to the IMU **1110**, or some combination thereof.

The locators **1108** are traced by an external imaging device of a virtual reality system, such that the virtual reality system can track the location and orientation of the entire HMD **1100**. Information generated by the IMU **1110** and the position sensors **1112** may be compared with the position and orientation obtained by tracking the locators **1108**, for improved tracking accuracy of position and orientation of the HMD **1100**. Accurate position and orientation is important for presenting appropriate virtual scenery to the user as the latter moves and turns in 3D space.

The HMD **1100** may further include a depth camera assembly (DCA) **1111**, which captures data describing depth information of a local area surrounding some or all of the HMD **1100**. To that end, the DCA **1111** may include a laser radar (LIDAR), or a similar device. The depth information may be compared with the information from the IMU **1110**, for better accuracy of determination of position and orientation of the HMD **1100** in 3D space.

The HMD **1100** may further include an eye tracking system **1114** for determining orientation and position of user's eyes in real time. The obtained position and orientation of the eyes also allows the HMD **1100** to determine the gaze direction of the user and to adjust the image generated by the display system **1180** accordingly. In one embodiment, the vergence, that is, the convergence angle of the user's eyes gaze, is determined. The determined gaze direction and vergence angle may also be used for real-time compensation of visual artifacts dependent on the angle of view and eye position. Furthermore, the determined vergence and gaze angles may be used for interaction with the user, highlighting objects, bringing objects to the foreground, creating additional objects or pointers, etc. An audio system may also be provided including e.g. a set of small speakers built into the front body **1102**.

Turning to FIG. **11**B, an AR/VR system **1150** is an example implementation of a wearable display system. The AR/VR system **1150** includes the HMD **1100** of FIG. **11**A, an external console **1190** storing various AR/VR applications, setup and calibration procedures, 3D videos, etc., and an input/output (I/O) interface **1115** for operating the console **1190** and/or interacting with the AR/VR environment. The HMD **1100** may be "tethered" to the console **1190** with a physical cable, or connected to the console **1190** via a wireless communication link such as Bluetooth®, Wi-Fi, etc. There may be multiple HMDs **1100**, each having an associated I/O interface **1115**, with each HMD **1100** and I/O interface(s) **1115** communicating with the console **1190**. In alternative configurations, different and/or additional components may be included in the AR/VR system **1150**. Additionally, functionality described in conjunction with one or more of the components shown in FIGS. **11**A and **11**B may be distributed among the components in a different manner than described in conjunction with FIGS. **11**A and **11**B in some embodiments. For example, some or all of the functionality of the console **1115** may be provided by the HMD **1100**, and vice versa. The HMD **1100** may be provided with a processing module capable of achieving such functionality.

As described above with reference to FIG. **11**A, the HMD **1100** may include the eye tracking system **1114** (FIG. **11**B) for tracking eye position and orientation, determining gaze angle and convergence angle, etc., the IMU **1110** for determining position and orientation of the HMD **1100** in 3D space, the DCA **1111** for capturing the outside environment, the position sensor **1112** for independently determining the position of the HMD **1100**, and the display system **1180** for displaying AR/VR content to the user. The display system **1180** includes (FIG. **11**B) an electronic display **1125**, for example and without limitation, a liquid crystal display (LCD), an organic light emitting display (OLED), an inorganic light emitting display (ILED), an active-matrix organic light-emitting diode (AMOLED) display, a transparent organic light emitting diode (TOLED) display, a projector, or a combination thereof. The display system **1180** further includes an optics block **1130**, whose function is to convey the images generated by the electronic display **1125** to the user's eye. The optics block may include various lenses, e.g. a refractive lens, a Fresnel lens, a diffractive lens, an active or passive Pancharatnam-Berry phase (PBP) lens, a liquid lens, a liquid crystal lens, etc., a pupil-replicating waveguide, grating structures, coatings, etc. The display system **1180** may further include a varifocal module **1135**, which may be a part of the optics block **1130**. The function of the varifocal module **1135** is to adjust the focus of the optics block **1130** e.g. to compensate for vergence-accommodation conflict, to correct for vision defects of a particular user, to offset aberrations of the optics block **1130**, etc.

The I/O interface **1115** is a device that allows a user to send action requests and receive responses from the console **1190**. An action request is a request to perform a particular action. For example, an action request may be an instruction to start or end capture of image or video data or an instruction to perform a particular action within an application. The I/O interface **1115** may include one or more input devices, such as a keyboard, a mouse, a game controller, or any other suitable device for receiving action requests and communicating the action requests to the console **1190**. An action request received by the I/O interface **1115** is communicated to the console **1190**, which performs an action corresponding to the action request. In some embodiments, the I/O interface **1115** includes an IMU that captures calibration data indicating an estimated position of the I/O interface **1115** relative to an initial position of the I/O interface **1115**. In some embodiments, the I/O interface **1115** may provide haptic feedback to the user in accordance with instructions received from the console **1190**. For example, haptic feedback can be provided when an action request is received, or the console **1190** communicates instructions to the I/O interface **1115** causing the I/O interface **1115** to generate haptic feedback when the console **1190** performs an action.

The console **1190** may provide content to the HMD **1100** for processing in accordance with information received from one or more of: the IMU **1110**, the DCA **1111**, the eye tracking system **1114**, and the I/O interface **1115**. In the example shown in FIG. **11**B, the console **1190** includes an application store **1155**, a tracking module **1160**, and a processing module **1165**. Some embodiments of the console **1190** may have different modules or components than those described in conjunction with FIG. **11**B. Similarly, the functions further described below may be distributed among components of the console **1190** in a different manner than described in conjunction with FIGS. **11**A and **11**B.

The application store **1155** may store one or more applications for execution by the console **1190**. An application is a group of instructions that, when executed by a processor, generates content for presentation to the user. Content generated by an application may be in response to inputs received from the user via movement of the HMD **1100** or the I/O interface **1115**. Examples of applications include: gaming applications, presentation and conferencing applications, video playback applications, or other suitable applications.

The tracking module **1160** may calibrate the AR/VR system **1150** using one or more calibration parameters and may adjust one or more calibration parameters to reduce error in determination of the position of the HMD **1100** or the I/O interface **1115**. Calibration performed by the tracking module **1160** also accounts for information received from the IMU **1110** in the HMD **1100** and/or an IMU included in the I/O interface **1115**, if any. Additionally, if tracking of the HMD **1100** is lost, the tracking module **1160** may re-calibrate some or all of the AR/VR system **1150**.

The tracking module **1160** may track movements of the HMD **1100** or of the I/O interface **1115**, the IMU **1110**, or some combination thereof. For example, the tracking module **1160** may determine a position of a reference point of the HMD **1100** in a mapping of a local area based on information from the HMD **1100**. The tracking module **1160** may also determine positions of the reference point of the HMD **1100** or a reference point of the I/O interface **1115** using data indicating a position of the HMD **1100** from the IMU **1110** or using data indicating a position of the I/O interface **1115** from an IMU included in the I/O interface **1115**, respectively. Furthermore, in some embodiments, the tracking module **1160** may use portions of data indicating a position or the HMD **1100** from the IMU **1110** as well as representations of the local area from the DCA **1111** to predict a future location of the HMD **1100**. The tracking module **1160** provides the estimated or predicted future position of the HMD **1100** or the I/O interface **1115** to the processing module **1165**.

The processing module **1165** may generate a 3D mapping of the area surrounding some or all of the HMD **1100** ("local area") based on information received from the HMD **1100**. In some embodiments, the processing module **1165** determines depth information for the 3D mapping of the local area based on information received from the DCA **1111** that is relevant for techniques used in computing depth. In various embodiments, the processing module **1165** may use the depth information to update a model of the local area and generate content based in part on the updated model.

The processing module **1165** executes applications within the AR/VR system **1150** and receives position information, acceleration information, velocity information, predicted future positions, or some combination thereof, of the HMD **1100** from the tracking module **1160**. Based on the received information, the processing module **1165** determines content to provide to the HMD **1100** for presentation to the user. For example, if the received information indicates that the user has looked to the left, the processing module **1165** generates content for the HMD **1100** that mirrors the user's movement in a virtual environment or in an environment augmenting the local area with additional content. Additionally, the processing module **1165** performs an action within an application executing on the console **1190** in response to an action request received from the I/O interface **1115** and provides feedback to the user that the action was performed. The provided feedback may be visual or audible feedback via the HMD **1100** or haptic feedback via the I/O interface **1115**.

In some embodiments, based on the eye tracking information (e.g., orientation of the user's eyes) received from the eye tracking system **1114**, the processing module **1165** determines resolution of the content provided to the HMD **1100** for presentation to the user on the electronic display **1125**. The processing module **1165** may provide the content to the HMD **1100** having a maximum pixel resolution on the electronic display **1125** in a foveal region of the user's gaze. The processing module **1165** may provide a lower pixel resolution in other regions of the electronic display **1125**, thus lessening power consumption of the AR/VR system **1150** and saving computing resources of the console **1190** without compromising a visual experience of the user. In some embodiments, the processing module **1165** can further use the eye tracking information to adjust where objects are displayed on the electronic display **1125** to prevent vergence-accommodation conflict and/or to offset optical distortions and aberrations.

Embodiments of the present disclosure may include, or be implemented in conjunction with, an artificial reality system. An artificial reality system adjusts sensory information about outside world obtained through the senses such as visual information, audio, touch (somatosensation) information, acceleration, balance, etc., in some manner before presentation to a user. By way of non-limiting examples, artificial reality may include virtual reality (VR), augmented reality (AR), mixed reality (MR), hybrid reality, or some combination and/or derivatives thereof. Artificial reality content may include entirely generated content or generated content combined with captured (e.g., real-world) content. The artificial reality content may include video, audio, somatic or haptic feedback, or some combination thereof. Any of this content may be presented in a single channel or in multiple channels, such as in a stereo video that produces a three-dimensional effect to the viewer. Furthermore, in some embodiments, artificial reality may also be associated with applications, products, accessories, services, or some combination thereof, that are used to, for example, create content in artificial reality and/or are otherwise used in (e.g., perform activities in) artificial reality. The artificial reality system that provides the artificial reality content may be implemented on various platforms, including a wearable display such as an HMD connected to a host computer system, a standalone HMD, a near-eye display having a form factor of eyeglasses, a mobile device or computing system, or any other hardware platform capable of providing artificial reality content to one or more viewers.

The hardware used to implement the various illustrative logics, logical blocks, modules, and circuits described in connection with the aspects disclosed herein may be implemented or performed with a general purpose processor, a digital signal processor (DSP), an application specific integrated circuit (ASIC), a field programmable gate array (FPGA) or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general-purpose processor may be a microprocessor, but, in the alternative, the processor may be any conventional processor, controller, microcontroller, or state machine. A processor may also be implemented as a combination of computing devices, e.g., a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration. Alternatively, some steps or methods may be performed by circuitry that is specific to a given function.

The present disclosure is not to be limited in scope by the specific embodiments described herein. Indeed, other various embodiments and modifications, in addition to those described herein, will be apparent to those of ordinary skill in the art from the foregoing description and accompanying drawings. Thus, such other embodiments and modifications are intended to fall within the scope of the present disclosure. Further, although the present disclosure has been described herein in the context of a particular implementation in a particular environment for a particular purpose, those of ordinary skill in the art will recognize that its usefulness is not limited thereto and that the present disclosure may be beneficially implemented in any number of environments for any number of purposes. Accordingly, the claims set forth below should be construed in view of the full breadth and spirit of the present disclosure as described herein.

What is claimed is:

1. A beam scanner comprising:

a first tiltable reflector for reflecting a light beam at a variable angle in a first plane;

a second tiltable reflector for reflecting the light beam at a variable angle in a second plane;

a beam-folded pupil relay for receiving the light beam from the first tiltable reflector and relaying the light beam to the second tiltable reflector, the beam-folded pupil relay comprising:

a beamsplitter for receiving the light beam reflected by the first tiltable reflector; and

a first curved reflector for receiving the light beam from the beamsplitter, and for reflecting the light beam back towards the beamsplitter, wherein the beamsplitter is configured to:

couple the light beam reflected by the first curved reflector to the second tiltable reflector; and

out-couple the light beam reflected by the second tiltable reflector.

2. The beam scanner of claim **1**, wherein the first curved reflector has a radius of curvature substantially equal to an optical path length from the first tiltable reflector to the first curved reflector, and to an optical path length from the second tiltable reflector to the first curved reflector.

3. The beam scanner of claim **1**, wherein the beamsplitter comprises a polarization beamsplitter (PBS) configured to reflect light having a first polarization state and to transmit light having a second polarization state orthogonal to the first polarization state, the beam scanner further comprising:

a first quarter-wave waveplate (QWP) disposed in an optical path between the PBS and the first curved reflector and configured to convert polarization of the light beam upon double pass through the first QWP between the first and second polarization states; and

a second QWP disposed in an optical path between the PBS and the second tiltable reflector and configured to convert polarization of the light beam upon double pass through the second QWP between the first and second polarization states.

4. The beam scanner of claim **3**, further comprising:

a second curved reflector configured to:

receive the light beam from the beamsplitter after reflection from the first and second tiltable reflectors; and

reflect the light beam to an exit pupil of the beam scanner; and

a third QWP disposed in an optical path between the beamsplitter and the second curved reflector and configured to convert polarization of the light beam propagated therethrough to a circular polarization.

5. The beam scanner of claim **4**, wherein the first curved reflector and the first tiltable reflector are disposed on opposite sides of the beamsplitter, and wherein the second curved reflector and the second tiltable reflector are disposed on opposite sides of the beamsplitter.

6. The beam scanner of claim **4**, further comprising:

a first lens in an optical path between the first tiltable reflector and the PBS, for collimating the light beam impinging onto the first tiltable reflector; and

a second lens in an optical path between the second tiltable reflector and the PBS, for collimating the light beam impinging onto the second tiltable reflector.

7. The beam scanner of claim **4**, wherein the first and second curved reflectors each comprise a meniscus lens having a proximal concave surface and a distal convex surface, and a reflective coating at the distal convex surface.

8. The beam scanner of claim **7**, wherein the light beam comprises first and second color channel components, and wherein the reflective coating of at least one of the first or second curved reflectors includes a first dichroic coating for reflecting the first color channel component and a second coating for reflecting the second color channel component, wherein the first dichroic coating and the second coating are disposed at different distances from the proximal concave surface of the meniscus lens.

9. The beam scanner of claim **1**, wherein the first and second tiltable reflectors each comprise a tiltable microelectromechanical system (MEMS) reflector.

10. A projector comprising:

a light source for providing a light beam; and

a beam scanner coupled to the light source for receiving the light beam, the beam scanner comprising:

a first tiltable reflector for reflecting the light beam at a variable angle in a first plane;

a second tiltable reflector for reflecting the light beam at a variable angle in a second plane;

a beam-folded pupil relay for receiving the light beam from the first tiltable reflector and relaying the light beam to the second tiltable reflector, the beam-folded pupil relay comprising:

a beamsplitter for receiving the light beam reflected by the first tiltable reflector; and

a first curved reflector for receiving the light beam from the beamsplitter, and for reflecting the light beam back towards the beamsplitter, wherein the beam-folded pupil relay beamsplitter is configured to:

couple the light beam reflected by the first curved reflector to the second tiltable reflector; and

out-couple the light beam reflected by the second tiltable reflector.

11. The projector of claim **10**, wherein the beamsplitter comprises a polarization beamsplitter (PBS) configured to reflect light having a first polarization state and to transmit light having a second polarization state orthogonal to the first polarization state, the beam scanner further comprising:

a first quarter-wave waveplate (QWP) disposed in an optical path between the PBS and the first curved reflector and configured to convert polarization of the light beam upon double pass through the first QWP between the first and second polarization states; and

a second QWP disposed in an optical path between the PBS and the second tiltable reflector and configured to convert polarization of the light beam upon double pass through the second QWP between the first and second polarization states.

12. The projector of claim **11**, wherein the beam scanner further comprises:

a second curved reflector configured to:

receive the light beam from the beamsplitter after reflection from the first and second tiltable reflectors; and

reflect the light beam to an exit pupil of the beam scanner; and

a third QWP disposed in an optical path between the beamsplitter and the second curved reflector and configured to convert polarization of the light beam propagated therethrough to a circular polarization.

13. The projector of claim **12**, wherein:

the first curved reflector and the first tiltable reflector are disposed on opposite sides of the beamsplitter;

the second curved reflector and the second tiltable reflector are disposed on opposite sides of the beamsplitter; and

the first curved reflector comprises an opening for coupling the light beam from the light source to the beamsplitter.

14. The projector of claim **13**, wherein the beam scanner further comprises:

a first lens in an optical path between the first tiltable reflector and the PBS, for collimating the light beam impinging onto the first tiltable reflector; and

a second lens in an optical path between the second tiltable reflector and the PBS, for collimating the light beam impinging onto the second tiltable reflector.

15. A near-eye display for providing an image in angular domain to an eyebox of the near-eye display, the near-eye display comprising:

a light source for providing a light beam;

a beam scanner coupled to the light source for receiving the light beam, the beam scanner comprising:

a first tiltable reflector for reflecting the light beam at a variable angle in a first plane;

a second tiltable reflector for reflecting the light beam at a variable angle in a second plane;

a beam-folded pupil relay for receiving the light beam from the first tiltable reflector and relaying the light beam to the second tiltable reflector, the beam-folded pupil relay comprising:

a beamsplitter for receiving the light beam reflected by the first tiltable reflector;

a first curved reflector for receiving the light beam from the beamsplitter, and for reflecting the light beam back towards the beamsplitter, wherein the beam-folded pupil relay is configured to couple the light beam reflected by the first curved reflector to the second tiltable reflector; and

a second curved reflector configured to receive the light beam from the beamsplitter after reflection from the first and second tiltable reflectors, and to reflect the light beam to an exit pupil of the beam scanner; and

a pupil-replicating waveguide comprising a polarization-selective input grating for coupling the light beam into the pupil-replicating waveguide, wherein the polarization-selective input grating is disposed proximate the exit pupil of the beam scanner for receiving the light beam reflected by the second curved reflector.

16. The near-eye display of claim **15**, wherein:

the first curved reflector and the first tiltable reflector are disposed on opposite sides of the beamsplitter;

the second curved reflector and the second tiltable reflector are disposed on opposite sides of the beamsplitter; and

the first curved reflector comprises an opening for coupling the light beam from the light source to the beamsplitter.

17. The near-eye display of claim **16**, wherein the beamsplitter comprises a polarization beamsplitter (PBS) configured to reflect light having a first polarization state and to transmit light having a second polarization state orthogonal to the first polarization state, the beam scanner further comprising:

a first quarter-wave waveplate (QWP) disposed in an optical path between the PBS and the first curved reflector and configured to convert polarization of the light beam upon double pass through the first QWP between the first and second polarization states;

a second QWP disposed in an optical path between the PBS and the second tiltable reflector and configured to convert polarization of the light beam upon double pass through the second QWP between the first and second polarization states; and

a third QWP disposed in an optical path between the beamsplitter and the second curved reflector and configured to convert polarization of the light beam propagated therethrough to a circular polarization of a first handedness;

wherein the polarization-selective input grating is configured to propagate substantially without diffraction circularly polarized light of the first handedness, and to diffract circularly polarized light of a second handedness opposite to the first handedness.

18. The near-eye display of claim **15**, wherein the polarization-selective input grating comprises a polarization volume hologram.

19. The near-eye display of claim **15**, further comprising a controller operably coupled to the light source and the first and second tiltable reflectors and configured to:

operate the first and second tiltable reflectors to cause the light beam at the exit pupil of the beam-folded pupil relay to have a beam angle corresponding to a pixel of an image to be displayed; and

operate the light source in coordination with operating the first and second tiltable reflectors, such that the light beam has brightness corresponding to the pixel of the image to be displayed.

20. The near-eye display of claim **19**, wherein the first and second tiltable reflectors are both tiltable about two axes, the near-eye display further comprising an eye tracker operably coupled to the controller and configured to determine a gaze direction of a user of the near-eye display, wherein the controller is further configured to:

operate the first tiltable reflector to scan the light beam to form an image in angular domain for displaying to the user;

use the eye tracker to determine the gaze direction of the user; and

operate the second tiltable reflector to shift a field of view towards the gaze direction of the user.

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